Pursuing EWK Symmetry Breaking at CDF

Standard Model EWK Symmetry Breaking

Status of Tevatron running

Top Quark properties

Top Mass measurement

Standard Model Higgs Searches

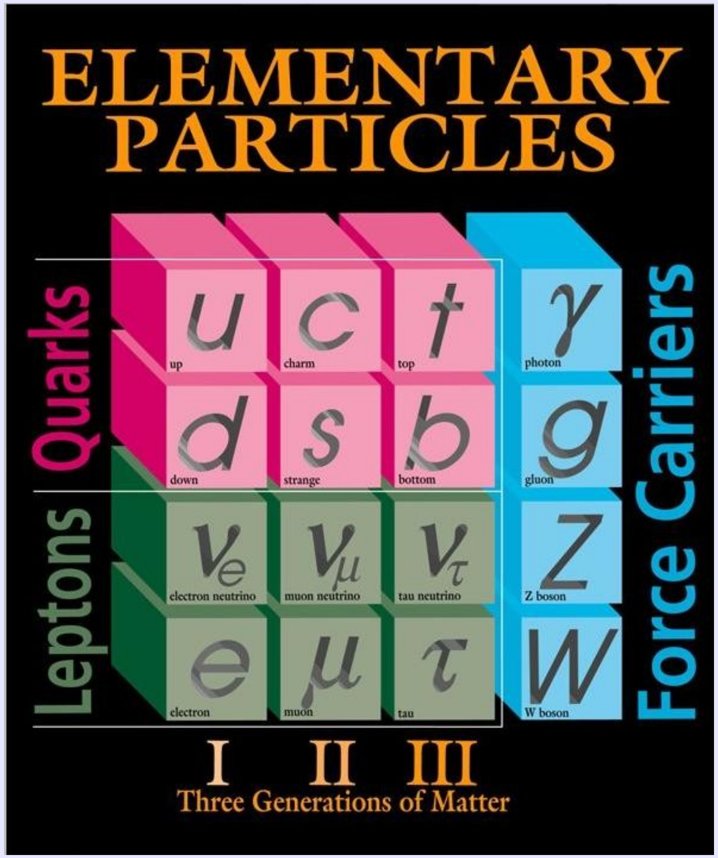
Summary

Standard Model

The model describes successfully all the experimental data .

What we know:

- $SU(3)\otimes SU(2)\otimes U(1)$ basic symmetry
- 3 generations of quarks and leptons
- EM, Weak and Strong Force



No BSM particles or forces seen

What we do not know:

- Why 3 generations?
- What distinguishes the 3 generations?
- How is the symmetry broken?
- What is the origin of mass?

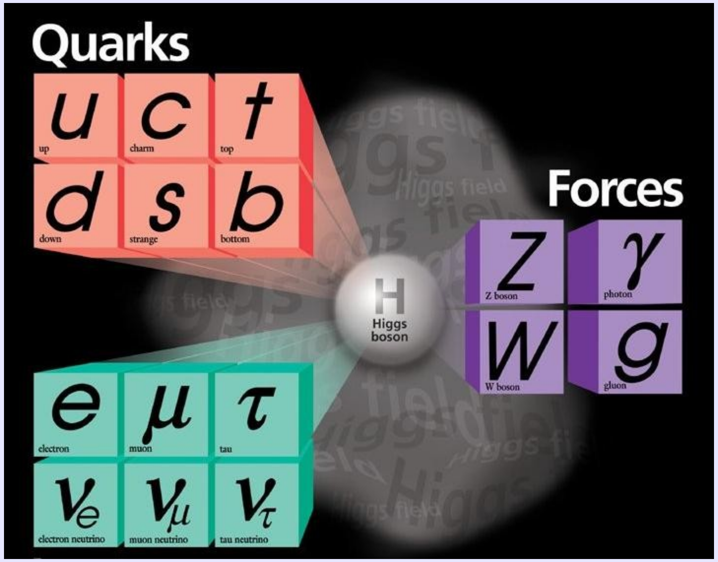
MANY OPEN QUESTIONS! Too many to list here !

Standard Model EWKSB

EWK theory unifies EM and Weak forces, but γ and W/Z masses are very different

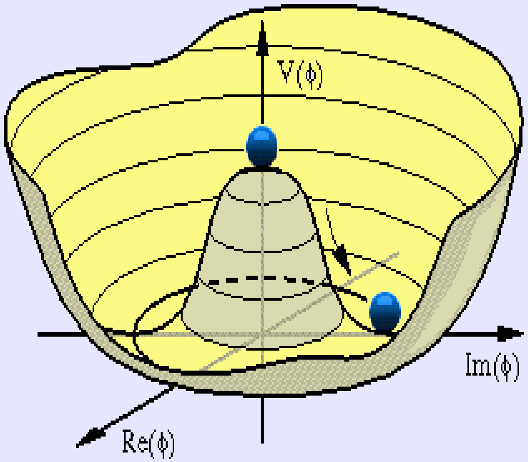
Higgs mechanism explains SB

- Gives masses to the Z and the $W^{\pm}$
- Gives masses to charged lepton and quarks through the Yukawa interaction.
- Predicts mixing among the generations
- Predicts the existence of the Higgs boson

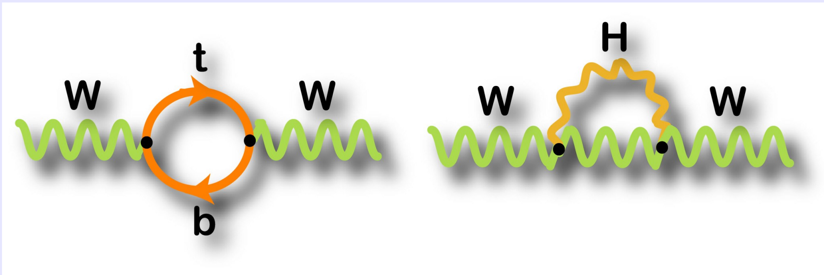


If the Higgs exist, new physics is necessary to stabilize its mass

Top is the heaviest quark. Yukawa coupling $g_t \sim 1$



Top Mass in the SM

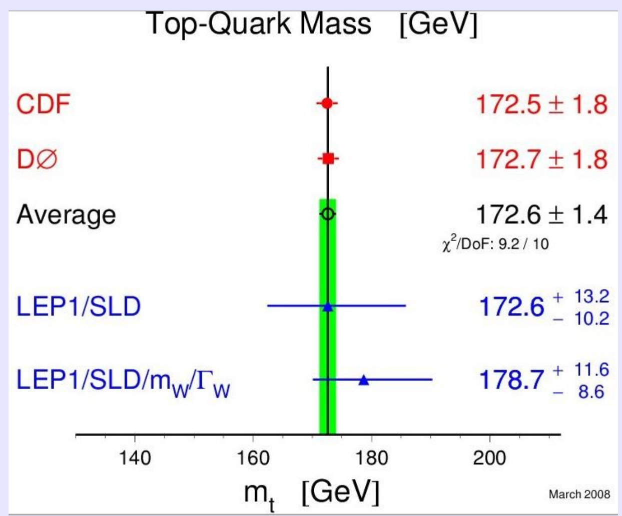


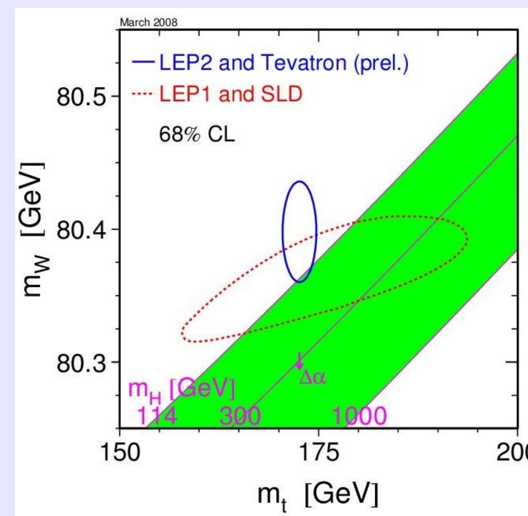
~ M_t^2 ~ $\log(M_H)$

- Quantum loop corrections to many EWK observables are sensitive to the top mass
- Top Mass is highly correlated to M_W and M_H in EWK theory

EWK fit using 15 SM precision measurements gives very large error on M_T and M_H

Addition of M_W and Γ_W reduces uncertainty

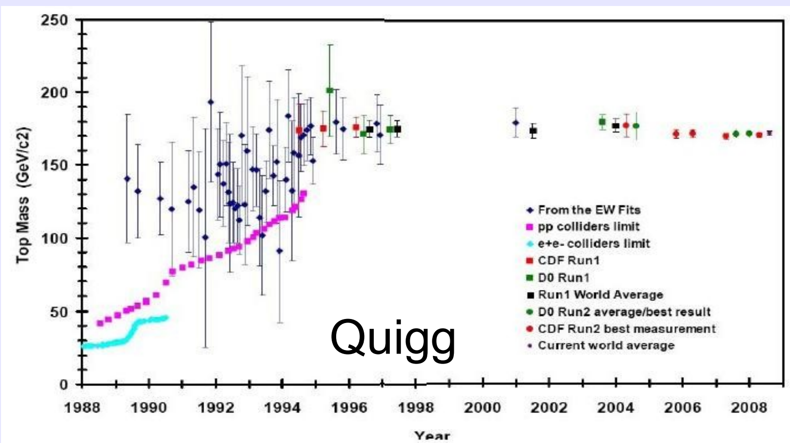




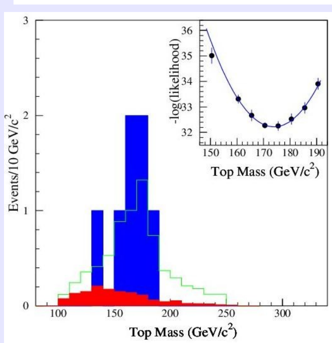
Top Mass and Higgs Searches

I will talk about the status of top mass measurements and Higgs searches at CDF, show also combined results with D0

Measurement error on M_T has improved since 1994



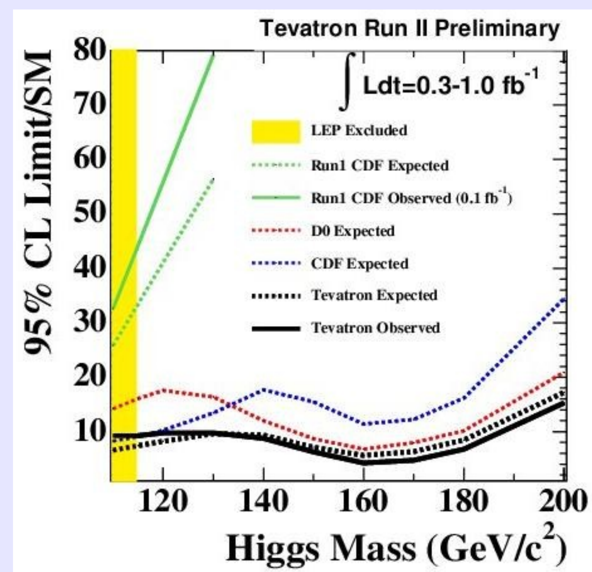
$$M_{top} = 174 \pm 10 \; ^{+13}_{-12} \; \mathrm{GeV}$$



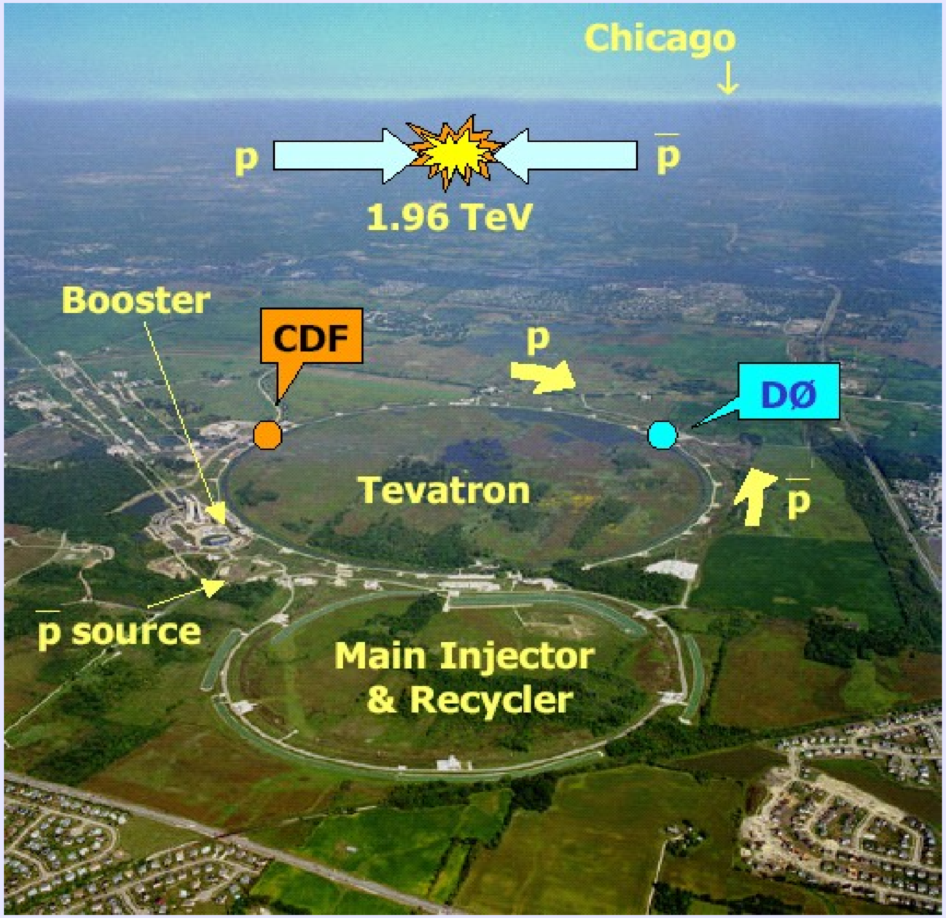
7 events
CDF 1994

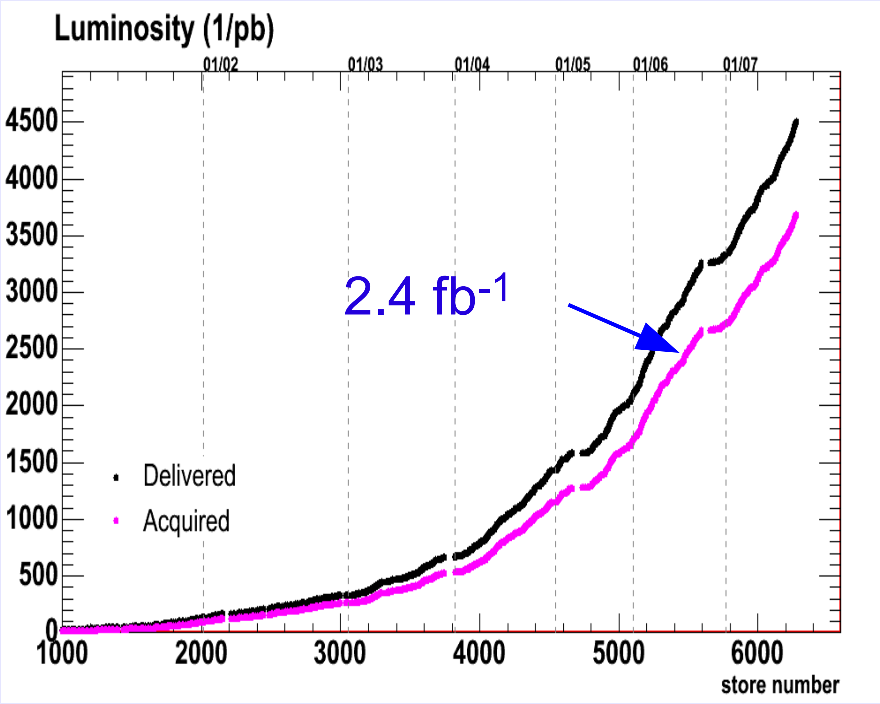
LEP direct search:
$M_H > 114$ GeV/c^2 @ 95% CL

Tevatron Run I and 2005
CDF-D0 combination limits



The Tevatron



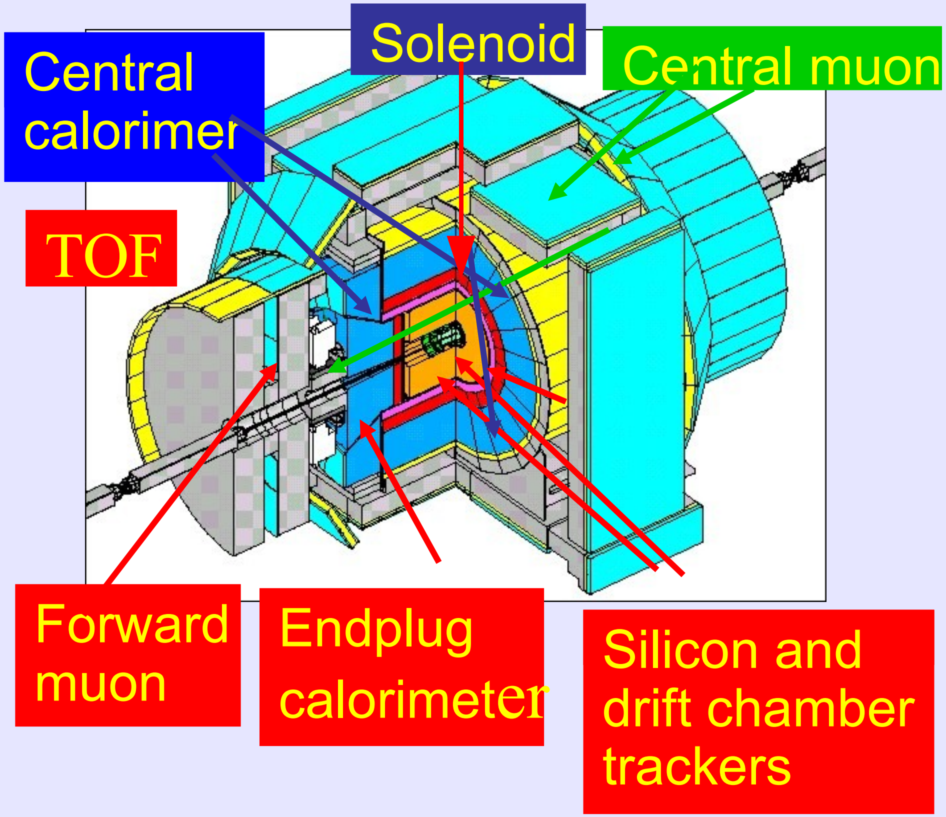


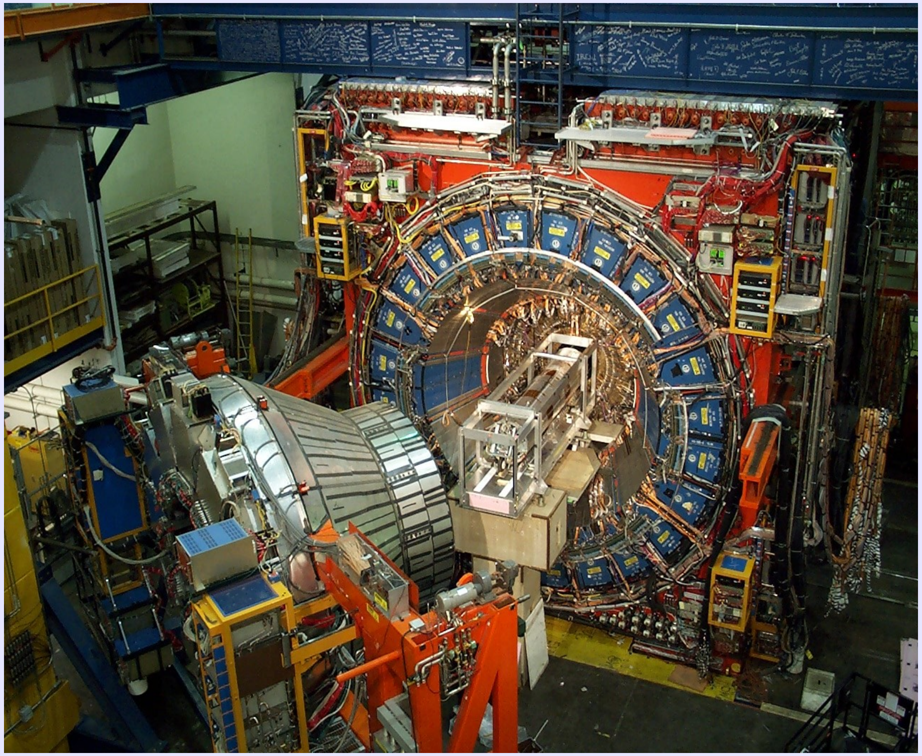
Tevatron has been doing very well.
Expect 6-7 fb^{-1} by end FY09

Record luminosity: 3.18×10^{32} cm^{-2} s^{-1}
July 5, 2008

Depending on funding, Tev will run through 2010: expect 7-9 fb^{-1}

CDF II Detector





Performance for precision mass measurements:

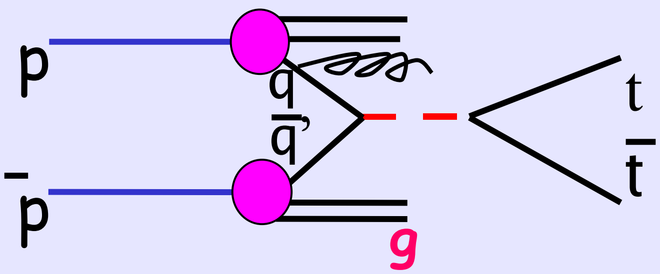
electrons: $13.5\%/\sqrt{E_T} \oplus 2\%$ in Central region

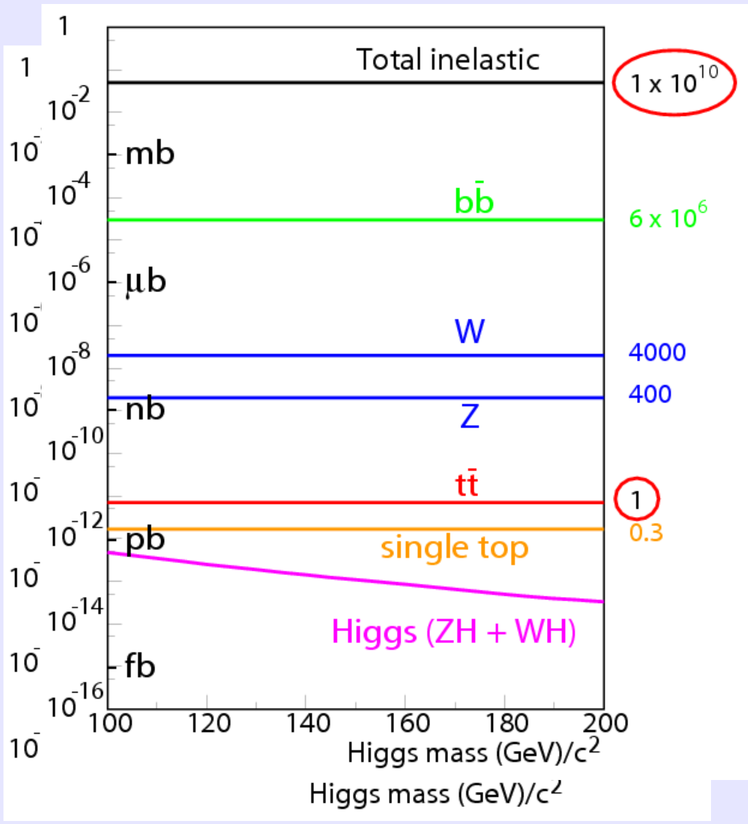
muons : $\sigma(p_T)/p_T = 0.1\%\ p_T$

jets : $(0.1 \mathrm{x} E_T + 1)$ GeV

Top Production and Decay

$t\bar{t}$ Production at the Tevatron:





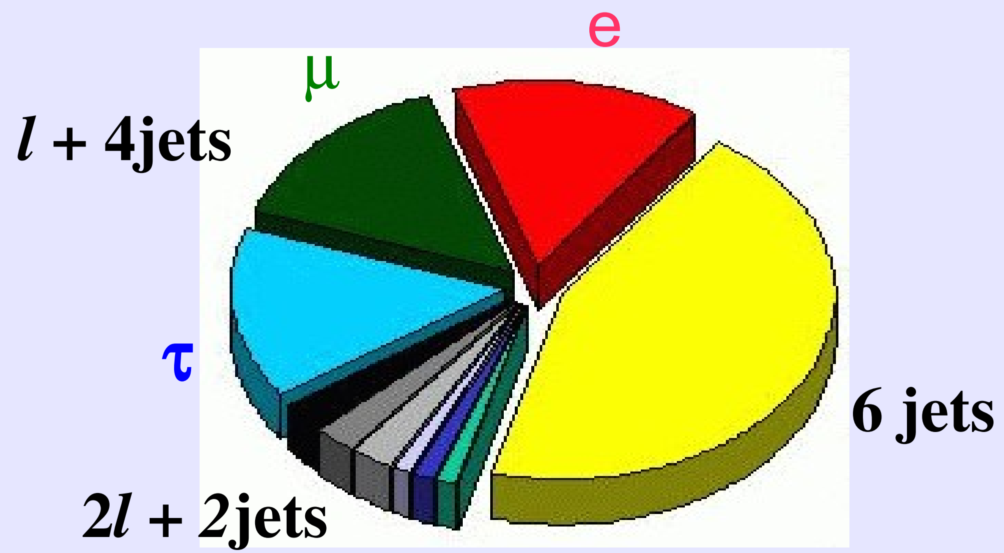
Top is heavy: decays very fast!

$$t\bar{t} \rightarrow W^{+} b\, W^{-} \bar{b}$$

$\Gamma(t \rightarrow Wb) \sim 1.5$ GeV, $t = 4\times10^{-25}$ sec

No hadronization

$t\bar{t}$ topologies



Backgrounds mostly from W and Z +jets production, some from single top

Top Quark Topologies

Reconstruct top events $t\bar{t} \rightarrow W^- b W^+ \bar{b}$

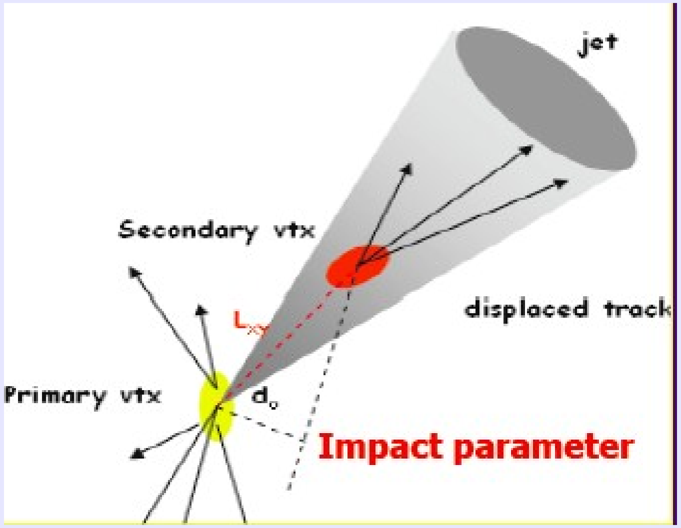
Many channels, depending on decay of the two W's
Events in 2 fb^{-1} after optimized selections

- Dilepton : 2 leptons, missing energy (2ν), 2 jets
  ~120 candidate events , S/B~1:1. S/B ~ 4:1 (≥ 1 b-tag, ~50 events)
- Lepton+jets : 1 lepton, missing energy (1ν), 4 jets
  ~370 candidate events, S/B ~ 4:1 (with ≥ 1 b-tag)
- All jets : 6 jets
  ~ 490 events , S/B ~ 2:3 (2 b-tags + NN selection)

Main requirements for top property measurements:

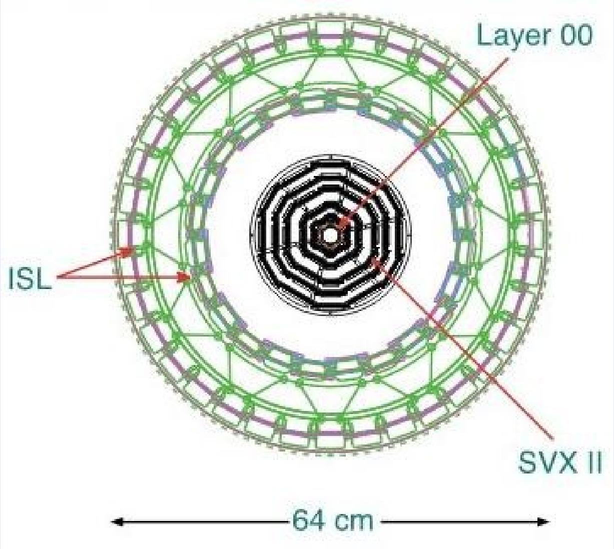
- Need tagging of b-jets to achieve the S/B ratio shown above.
- Need good jets reconstruction to reduce systematics from:
  detector effects, absolute Jet Energy Scale (JES), etc.

Tools: tagging of b-jets



7 layers of detectors in central region, starting at 2.5 cm ending at 22 cm.

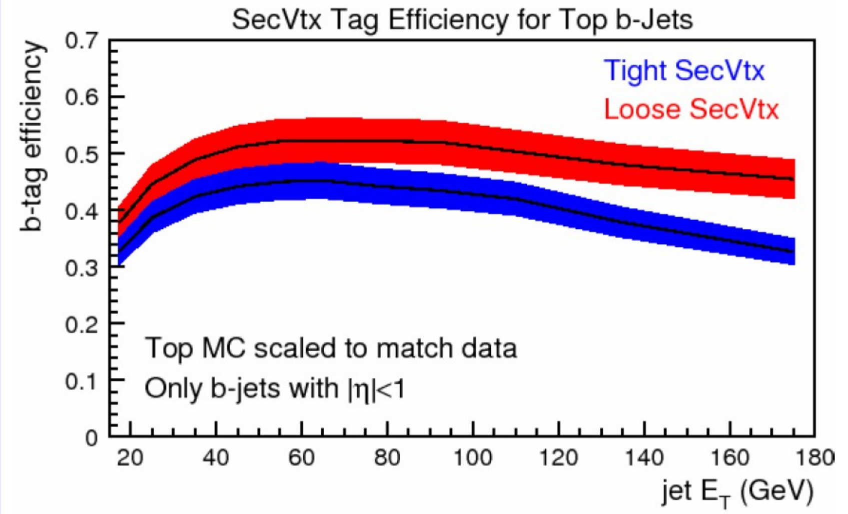
Good resolution on impact parameter. Allows displaced vertex tagging



Efficiency per b-jet = (40 ± 3)%
Efficiency for c-jet = (9 ± 2)%

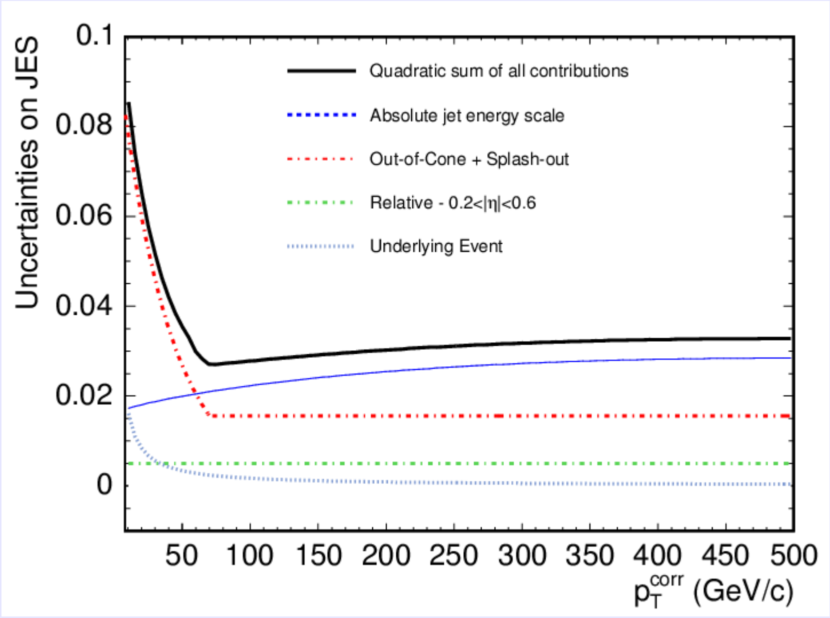
Effic. per top event = (60 ± 3)%
For $H \rightarrow b\bar{b}$, M=120 = (60 ± 3)%

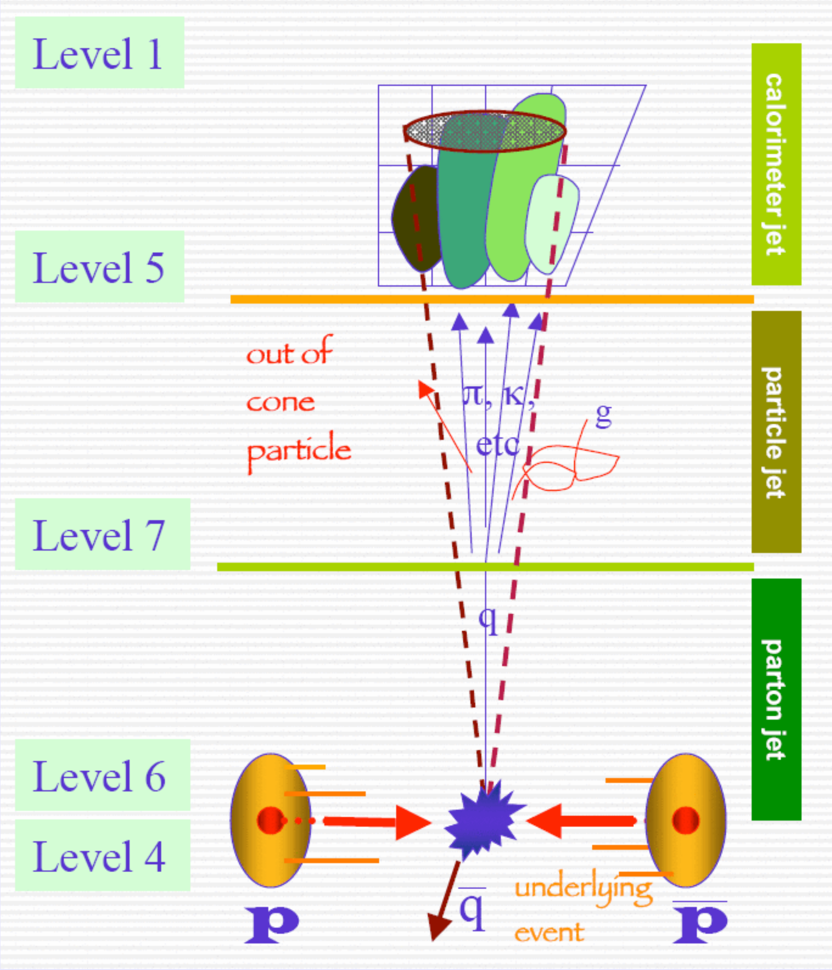
Mistag rate = (0.48 ± 0.04)%



Tools: Jet Reconstruction

- Use calorimeter information only
- Jet calibration done in many steps
- 3% systematics at high p_T





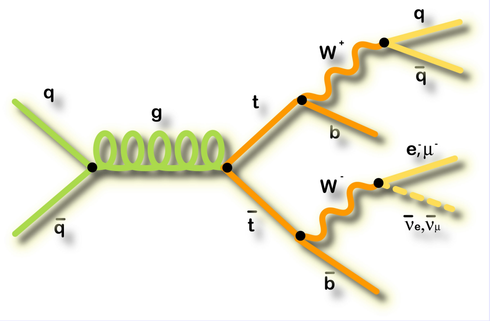
Source of the largest uncertainty on the top mass measurement

Use cone algorithm

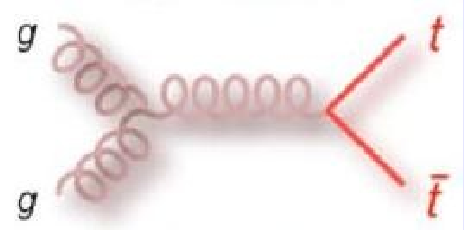
L+jets:Sample Composition

- Event Selection
  - Isolated lepton, $P_T > 20$ GeV
  - MET > 20 GeV (neutrino)
  - N (jets): only 4 jets with E_T >20 GeV
  - ≥1 b-tag by the SVX algorithm
- Background (mostly from Monte Carlo)
  - Mistag in W+light quarks
  - non-W QCD (from data)
  - Physics background: Wbb, Wcc
  - Single top, WW, WZ etc.

~85%



~15%



Background	1 b-tag	$\geq$ 2 b-tags
non-W QCD	13.8 ± 11.5	0.5 ± 1.5
W+q(mistag)+WW,WZ,ZZ	21.8 ± 3.6	0.8 ± 0.1
$W + b\bar{b}$, $c\bar{c}$, c	26.1 ± 10.2	3.4 ± 1.4
Single top	3.0 ± 0.2	0.9 ± 0.1
Total background	64.7 ± 16.3	5.5 ± 2.6
Predicted $t\bar{t}$ signal	182.6 ± 24.6	69.4 ± 11.2
Events observed	284	87

In 1.9 fb^{-1} find 371 events

Estimated background:

70 ± 17 events

But: are the top candidate events only top+SM background?

Is the Top Sample OK?

- Does top behave as a SM quark?

  Production cross section: predicted by QCD, EWK theory

  Top Decays: $t \rightarrow Wb$ expected ~ 100%,

W helicity (V-A)

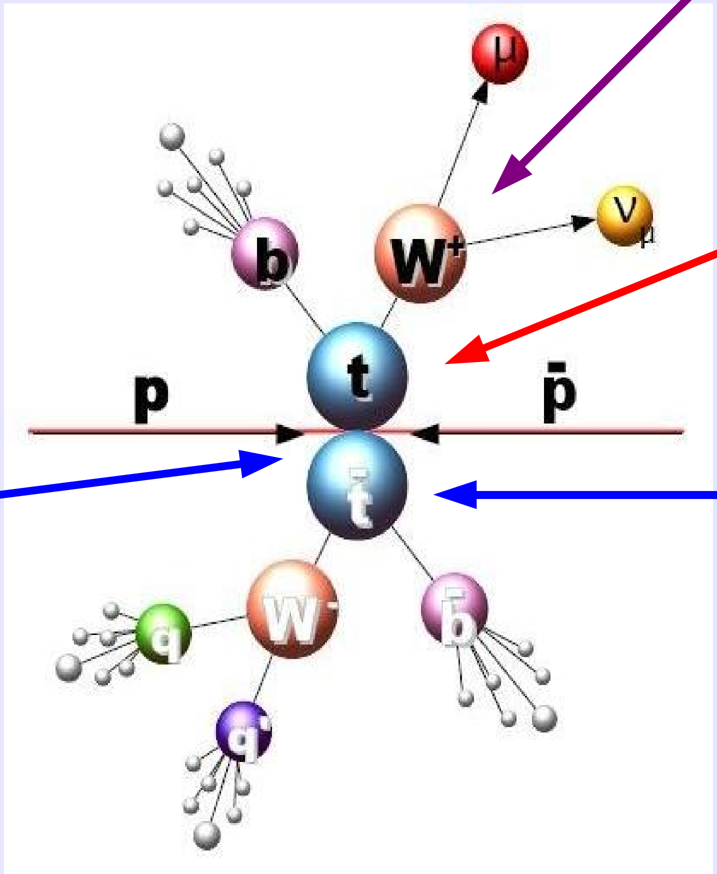
Production cross section:
$q\bar{q}'$ (85%), gg (15%)

Single Top production
via EWK processes

Spin Correlations

Resonance production

Non SM production



Mass, Spin,
Charge, Width

Branching ratios

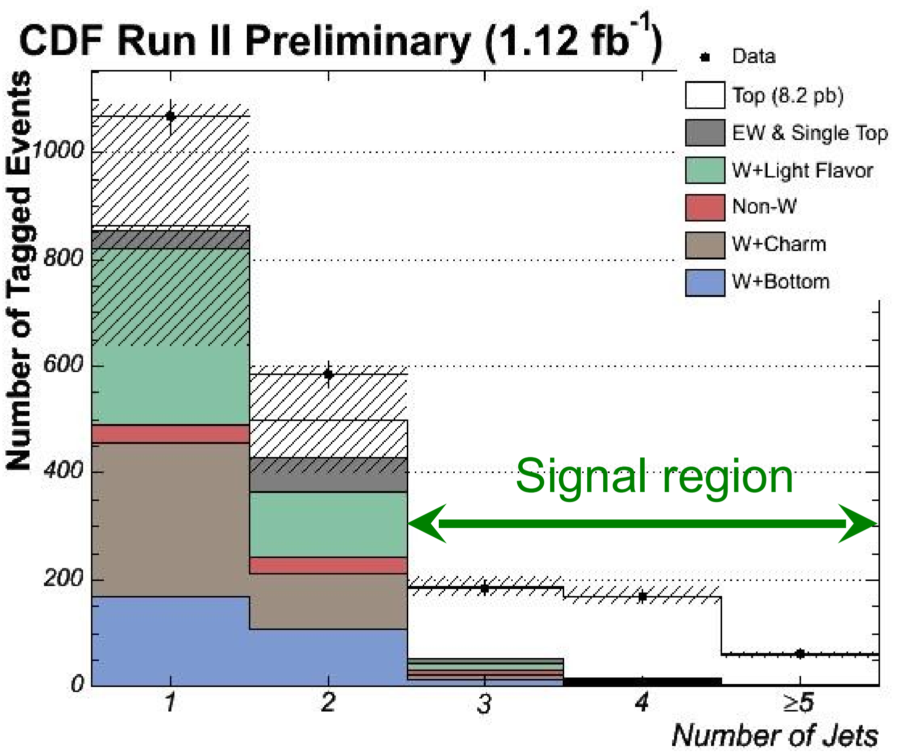
Top Physics studies

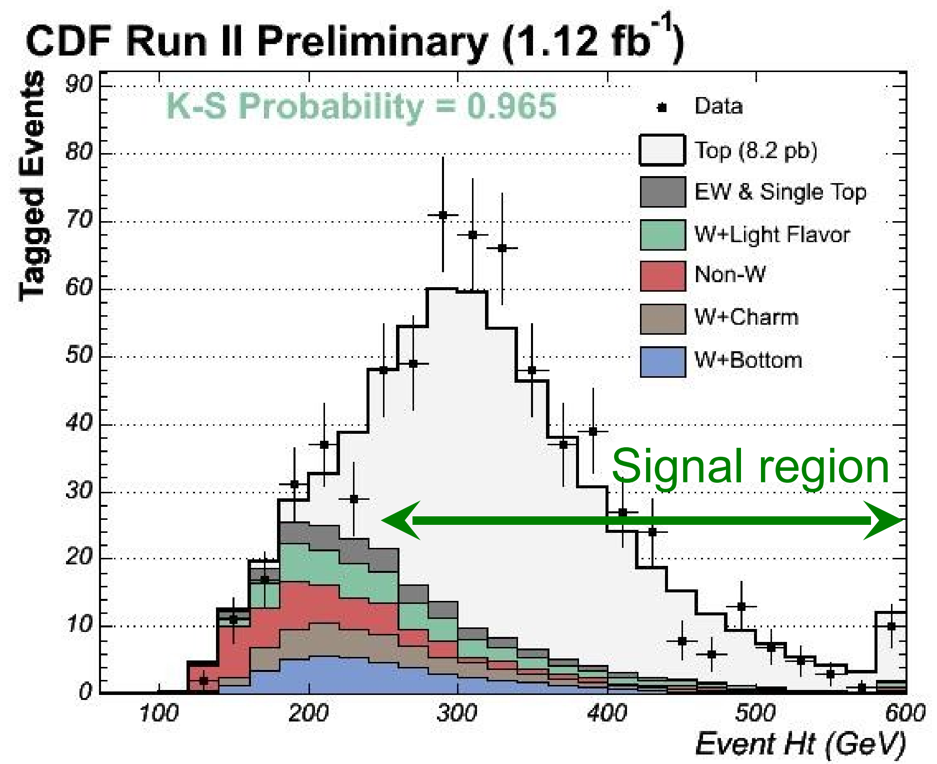
Checking production mechanism:

Standard Model
$t\bar{t}$ cross section
qq/gg production ratio
Single Top production
Forward-Backward Asymmetry

- New Physics
  X--> t t resonant production
  G(massive gluon) --> ttbar
  W'--> t b use single top sample
  t '--> search for heavy top-like quark.
  $\tilde{t}\ \tilde{t}$ --> stop pair production

Top Cross section (l+jets)





H_T>250 GeV
Missing E_T>30 GeV
≥1 tight tag

Counting experiment: $\sigma_{t\bar{t}} = \dfrac{N_{obs} - N_{bkg}}{(\epsilon_{tag} * SF)\left(\epsilon_{pretag} \int \mathcal{L}dt\right)}$

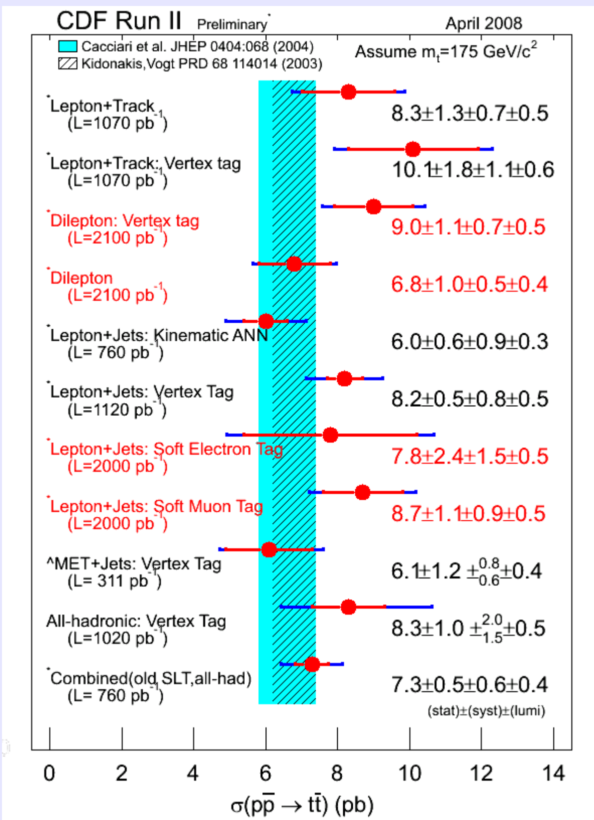
Signal region: 416 tags, 75± 15 bkg events

σ = 8.2 ± 0.5 (stat) ± 0.8 (sys) ± 0.5 (lumi) pb

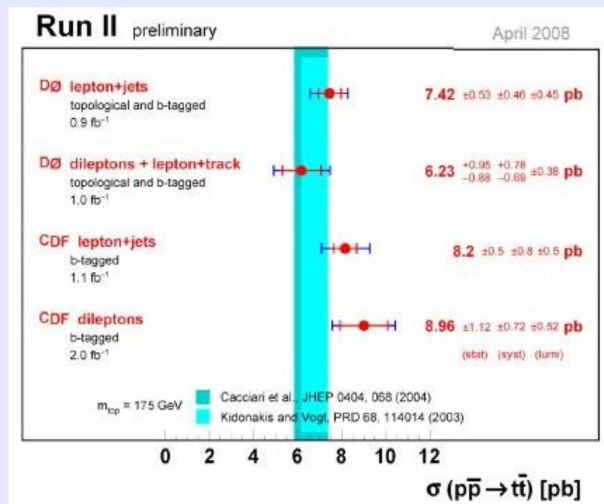
Top Cross Sections

CDF t t cross section measurements done in many channels, agree with QCD calculations.
Single top production agrees with EWK expectation

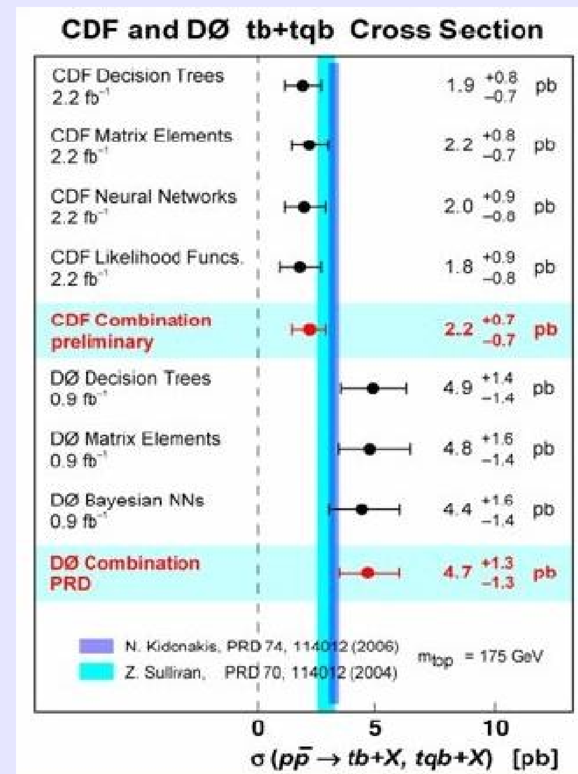
CDF σ(ttbar)



CDF-D0 results ttbar



Single Top production



Top Properties and Decays

Measurements on:

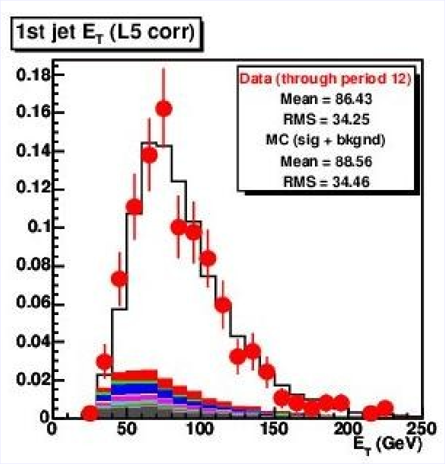
- Test SM properties
  - Top Charge
  - Branching ratios (V_{tb})
  - W helicity (V-A)

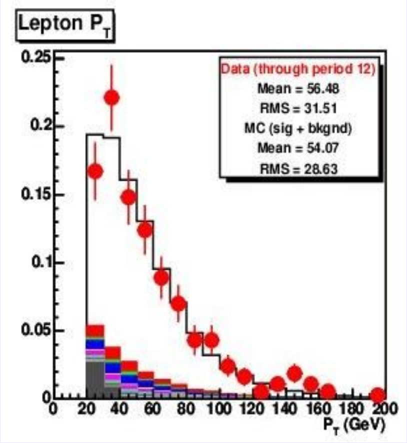
- Non SM decays
  - $t \rightarrow H^+ b$
  - $t \rightarrow Z\, q$ (FCNC)

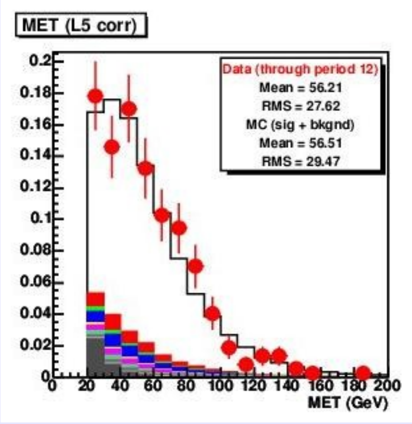
No evidence for deviations from Standard Model expectations found

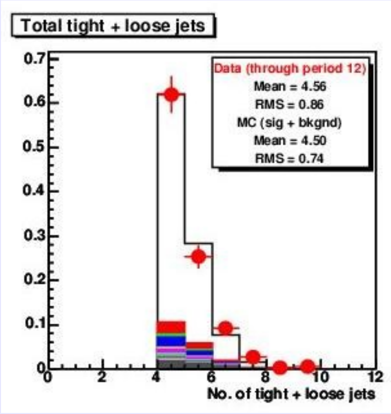
Top Mass Data sample

Comparison of data to signal+expected background obtained by Monte Carlo and data is very good.









Main challenge: reconstruct mass at the parton level

- We reconstruct $\bar{p}\, p \rightarrow t\, \bar{t} \rightarrow W\, b\, W\, b \rightarrow j_1\, j_2\, b\, l\, \nu\, b$
- We do not measure neutrino's. We measure jets, not quarks.
- Major systematics is in parton kinematics from jets (JES)
- Will use the $W \rightarrow j_1\, j_2$ to determine Δ_{JES} in "situ".

Top Mass Measurement ME(1)

- For each event we evaluate a likelihood as a function of the top mass and Δ_{JES} (related to the jets momenta measurements)
- All possible jet permutations are included with weights = wi.

$$L(\vec{y}\,|\,m_t, \Delta_{\mathrm{JES}}) = \frac{1}{N(m_t)}\frac{1}{A(m_t, \Delta_{\mathrm{JES}})}\sum_{i=1}^{24} w_i L_i(\vec{y}\,|\,m_t, \Delta_{\mathrm{JES}})$$

measured quantities **normalization** **acceptance** **24 Permutations**

$$L_i(\vec{y}\,|\,m_t, \Delta_{\mathrm{JES}}) = \int \frac{f(z_1)f(z_2)}{FF}\,\mathrm{TF}(\vec{y}\,|\,\vec{x}, \Delta_{\mathrm{JES}})\,|M(m_t, \vec{x})|^2\,d\Phi(\vec{x})$$

Incoming partons **Transfer functions** **parton level quantities**

- We integrate over phase space (d Φ) and Matrix Element (M) for t t production and decay.

Top Mass : integration (2)

- From 32 parameters in

  $z_1 + z_2 = q\, q'\, b_1 + \text{lep}\ \nu\ b_2$,

  assumptions on incoming partons, lepton masses, charged lepton P and energy-momentum conservation leave a 19-dimensional integration, performed by Quasi-Monte Carlo method.
- Integration variables:

  M_1^2 and M_2^2 , the hadronic and leptonic top mass squared

  m_1^2 and m_2^2 , the hadronic and leptonic W mass squared

  $\beta = \log(\rho_q/\rho_{q'})$, log of ratio of momenta of the two q from W

  $P_T(t\,t)$, priors from MC

  $\Delta\eta$ (parton-jet) , $\Delta\Phi$ (parton-jet) for each jet.

  Mass of each p-jet. All jet priors from MC

In situ calibration of JES (3)

- Likelihood parameters are m_t and Δ_{JES}

- We shift each jet by the factor

$$JES = 1 + \Delta_{JES} \times \sigma_{JES}(p_T,\eta)$$

where $\sigma_{JES}(p_T,\eta)$ is the systematic uncertainty on the jet p_T

- Δ_{JES} is determined using the decay

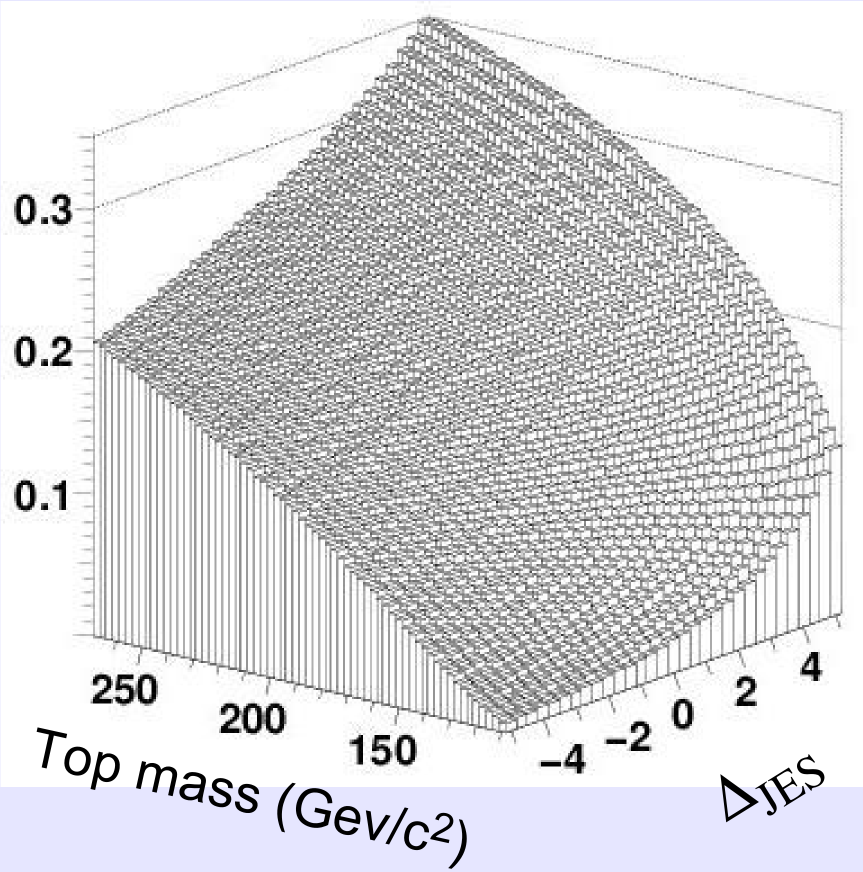
$$W \rightarrow j_1 j_2$$

and using the measured value for the W mass

- Precision on Δ_{JES} is determined by the statistics we have, thus a systematics uncertainty is now a statistical one

Top Mass: Acceptance (4)

$t\bar{t}$ acceptance



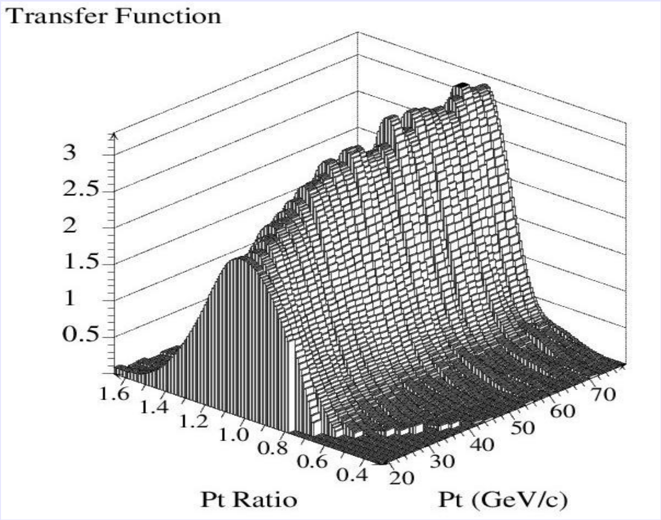
Strong dependence on the top mass and on Δ_{JES} and on $m_{t.}$

Due to the 20 GeV threshold on the 4 jets

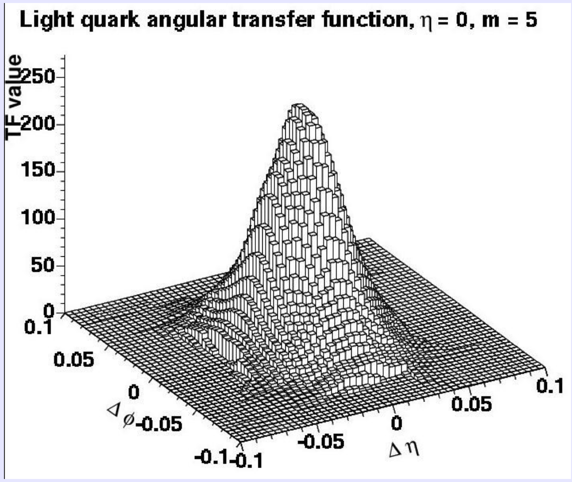
Top Mass: Transfer Functions (5)

- The transfer functions for a given parton x, give the probability that we observe y. Detector effects, resolutions etc. are included
- Both angular and P_T transfer functions are used
- Multiplied by efficiency for proper normalization
- Transfer functions depend on jet mass as well as on P_T (in η bins). Also they are evaluated for 25 values of Δ_{JES}.

P_T ratio= P_T(jet)/P_T(q)



P_T(q)=40 GeV, m_{jet}=30 GeV



Top Mass: include background(6)

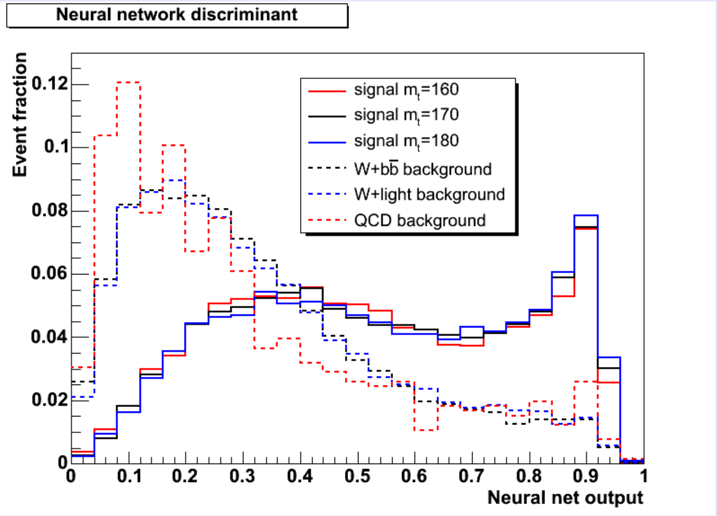
- Log(Likelihoods) for each event are added together
- Background ME is not used
- Background contribution is subtracted.

$$\log L_{\text{sig}} = \sum_i \left[\log L_i - f_{\text{bg}}(q_i) \log \overline{L(\text{background})} \right]$$

f_{bg} is the fraction of events like event i , which are background.

$f_{bg}(q) = B(q)/(S(q)+B(q))$

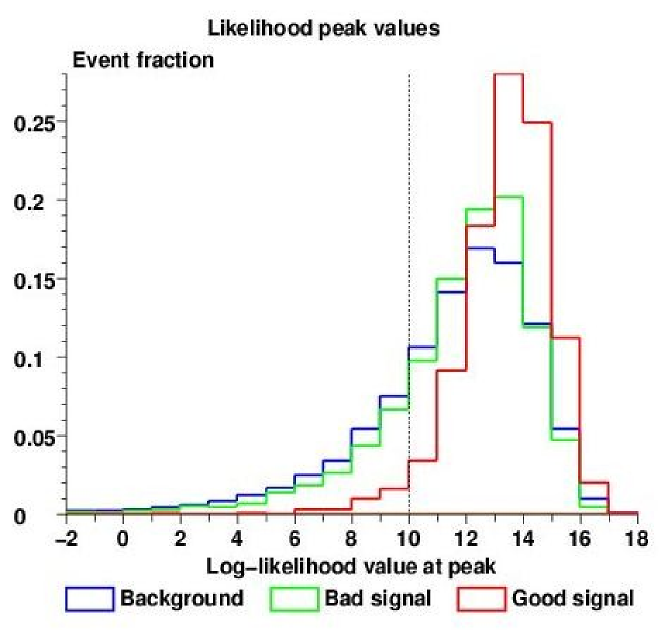
The NN discriminant uses 7 kinematic variables: p_T(of 4 jets), E_T(lepton), H_T, $\not{E}_T$ and 3 shape variables(Aplanarity, DR(j j)min, HTZ)



Top Mass: Likelihood cut(7)

After background subtraction we apply a cut on the final likelihood

- About 35% of the events do not behave according to our model:
  jets due to Initial or final state radiation
  W decays into taus
  contamination from other top topologies
- Background events have a low L tail



likelihood cut efficiency

Type of event	Total	1-tag	>1-tag
Good signal	96.6%	96.0%	98.0%
Bad signal	80.2%	80.5%	79.5%
Background	74.4%	74.5%	71.8%

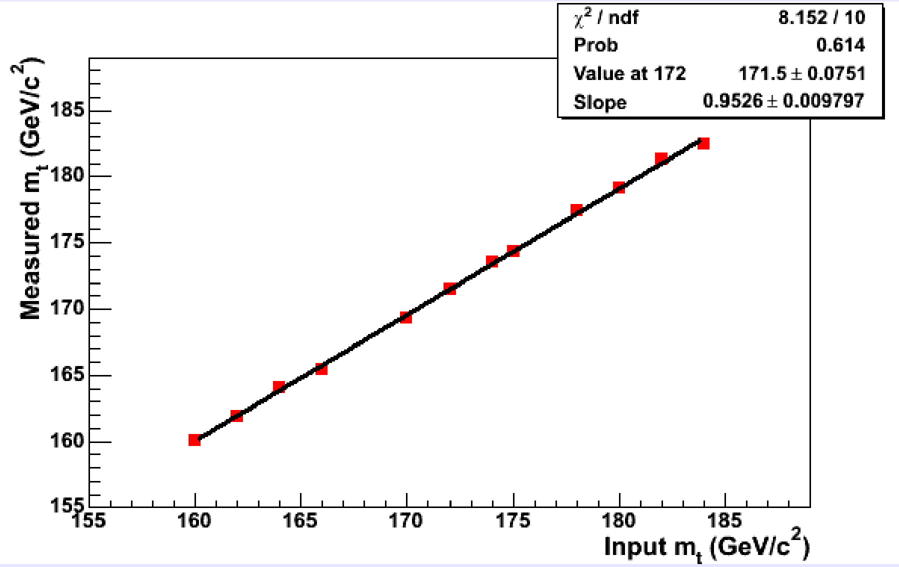
We loose only 3.4% signal events while rejecting 19.8% of bad signal and 25.6% of background

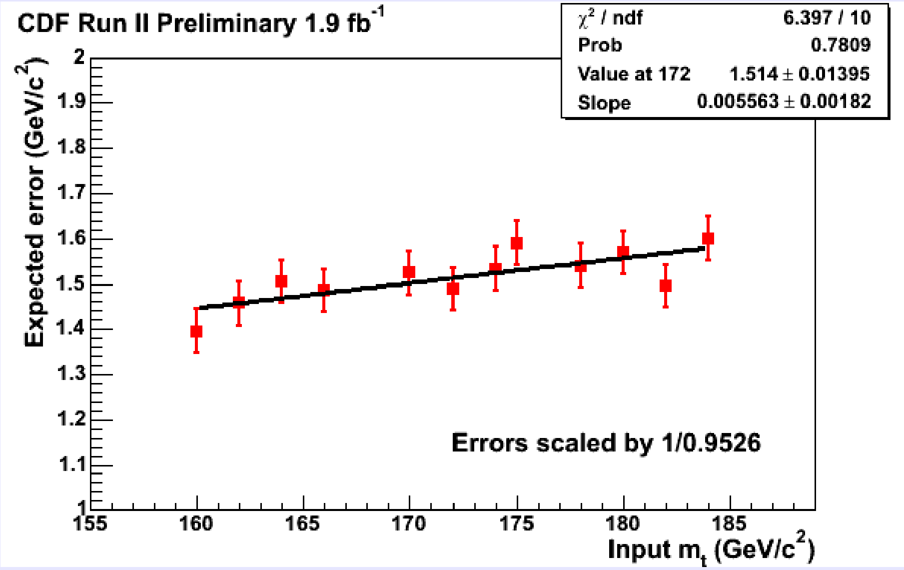
Top Mass: MC Calibration(8)

We use 12 mass point between 160 and 185 GeV/c^2 to calibrate the method

M_{meas} =(0.953± 0.009) × m_{input}

$\delta m(172)=1.5$ GeV/c^2



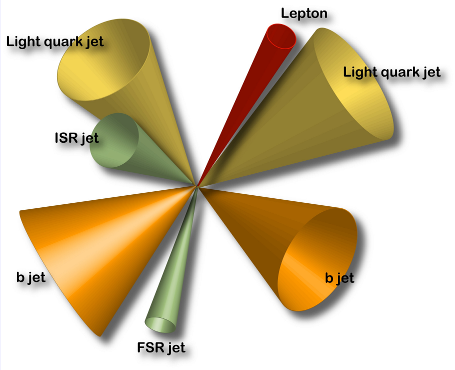


Top Mass: Systematics (9)

Systematics on the measurement:
 Method:
  calibration, background (3 terms)

Physics:
 MC generators, ISR/FSR,
 PDF's, background Q^2

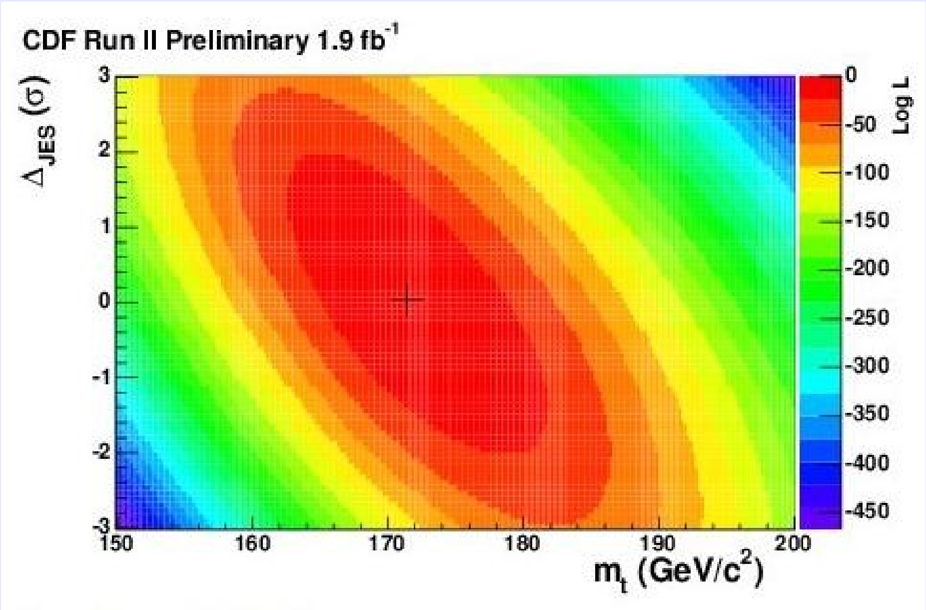
Detector:
 JES, lepton p_T, permutation
 weights, pileup



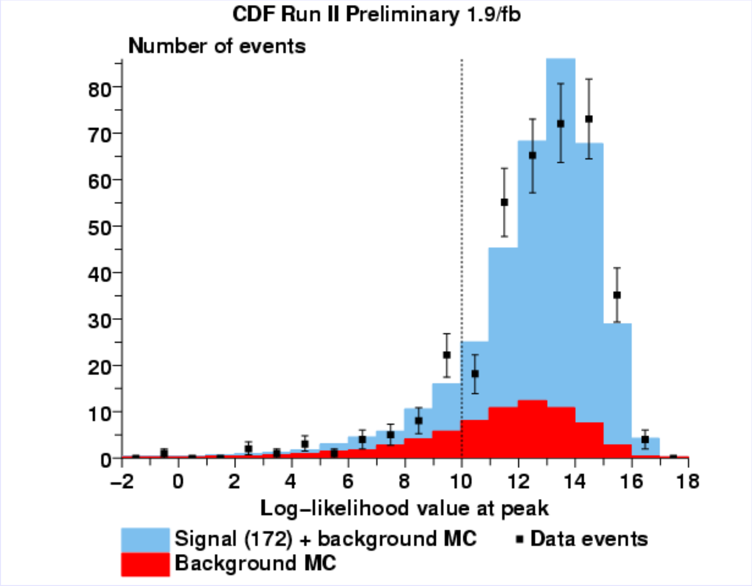
Systematic source	Δm_t (GeV/c^2)
Calibration	0.13
MC generator	0.37
ISR and FSR	0.50
Residual JES	0.60
b-JES	0.36
Lepton P_T	0.18
Permutation weights	0.01
Pileup	0.05
PDFs	0.41
Background: fraction	0.27
Backg: composition	0.24
Backg: average shape	0.04
Backg: Q^2	0.08
Total	1.11

Top Mass results (10)

2D likelihood from data (302 ev.)



Comparison of MC likelihood with data: quite good

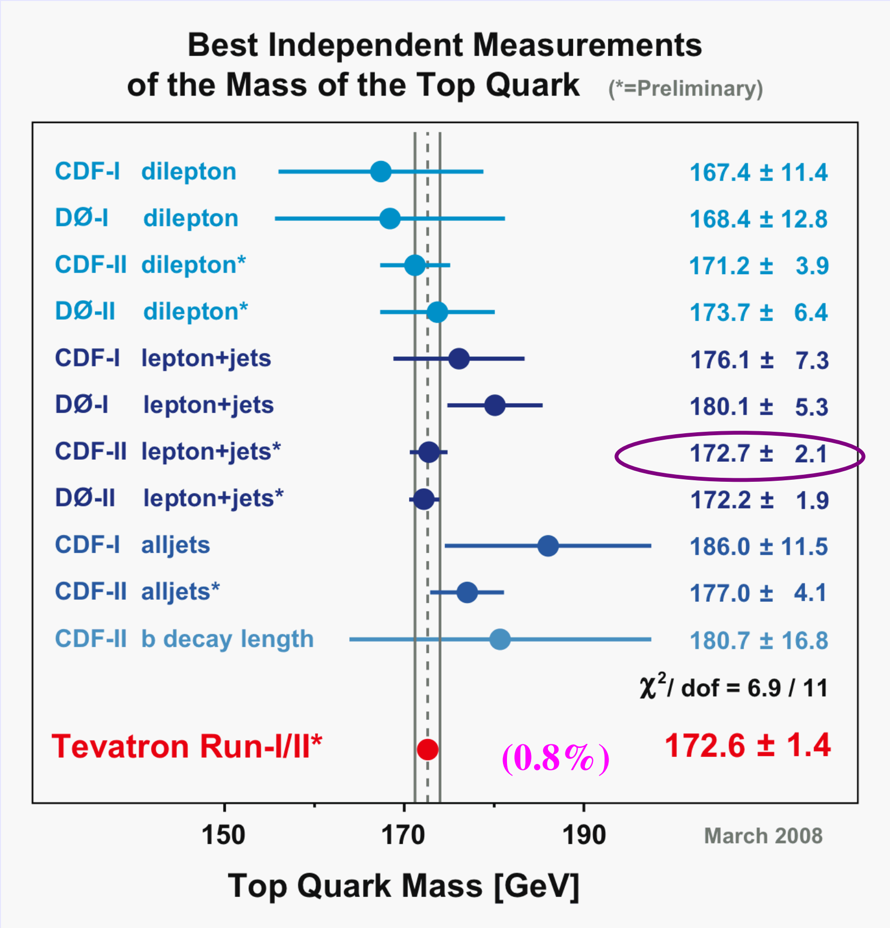


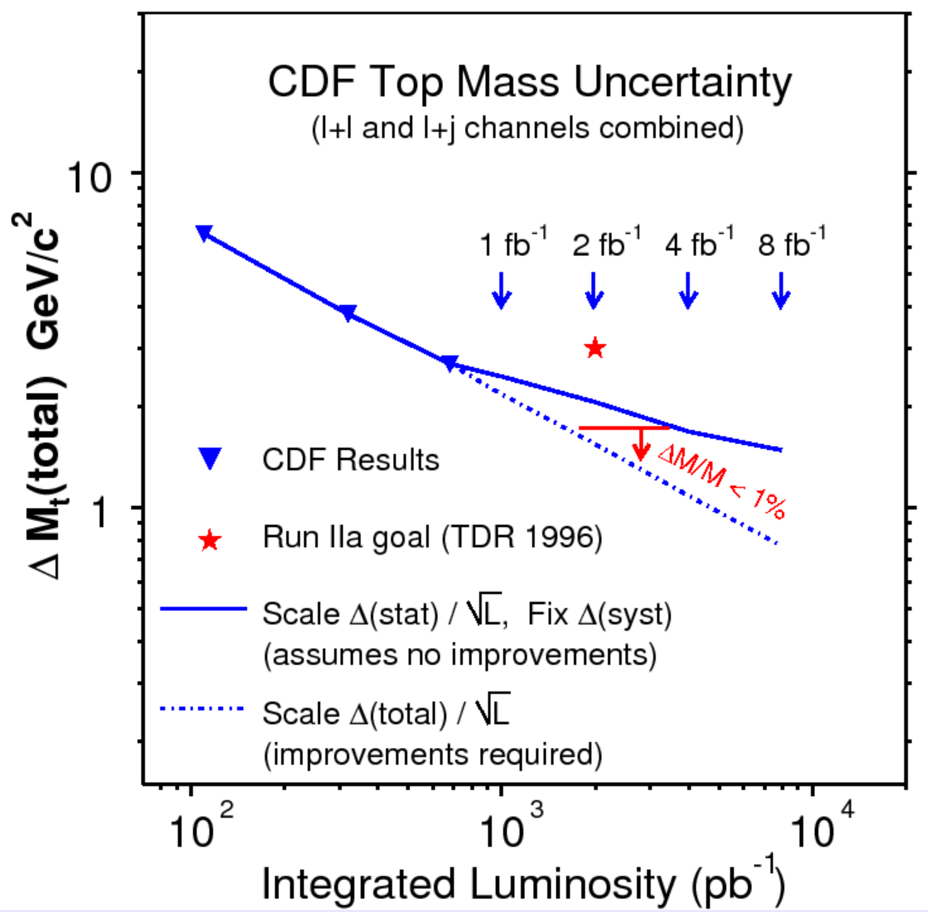
M_{top} = 171.4 ± 1.1 (stat.) ± 1.0 (JES) ± 1.1 (syst) GeV/c^2 = 171.4 ± 1.8 GeV/c^2

Also find Δ_{JES} = (0.03 ± 0.31), i.e., statistics limited

Best CDF mass measurement with 1.9 fb^{-1}

Top Mass summary





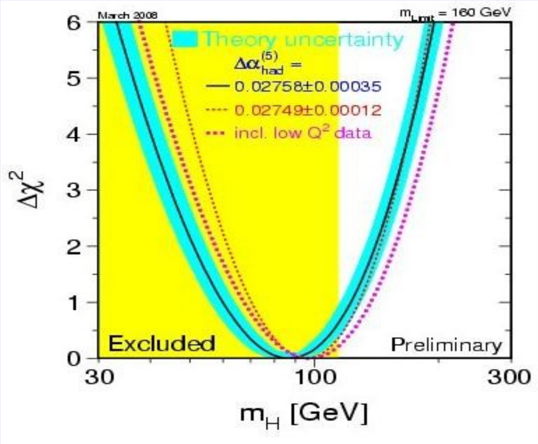
New measurement

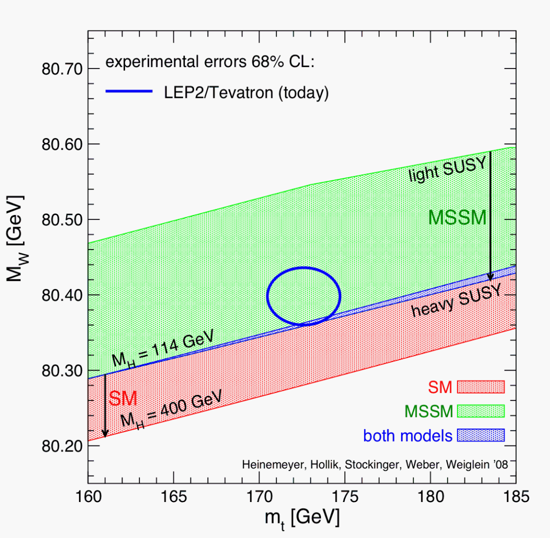
M_t=171.4 ± 1.8 GeV/c^2

not yet included

EWK Fit: Winter 2008

Winter Conferences EWK Fit, gives MH < 190 GeV/c^2





Winter 2008 best Fit

$M_H = 87^{+36}_{-27}$ GeV/c^2

and

$M_H <$ 160 GeV/c^2 at 95% CL

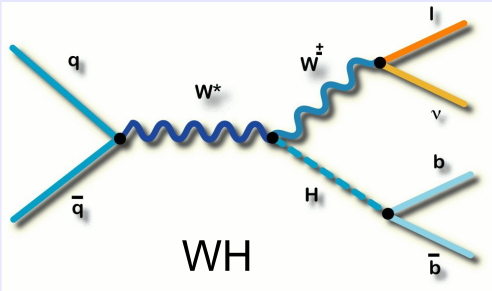
Direct limit:

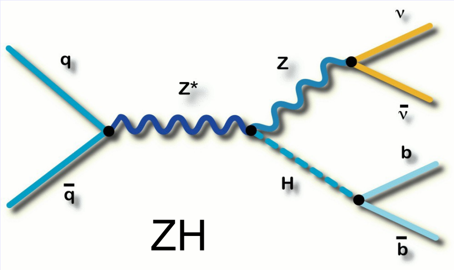
$M_H >$ 114 GeV at 95% CL

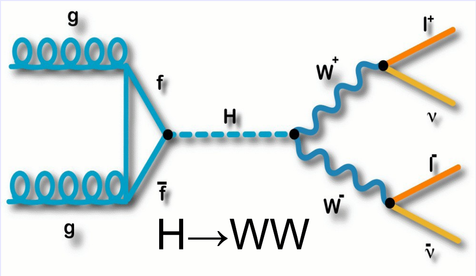
adding the direct limit

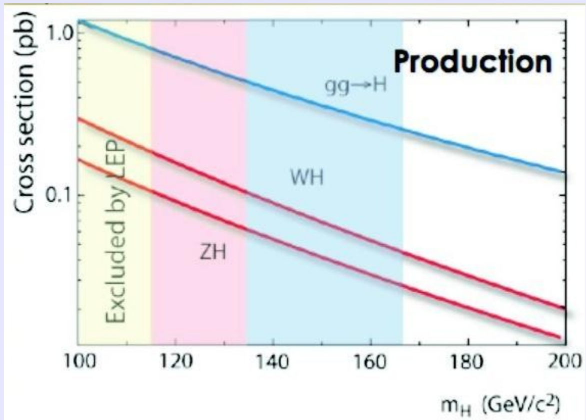
$M_H <$ 190 GeV/c^2 at 95% CL

SM Higgs Searches



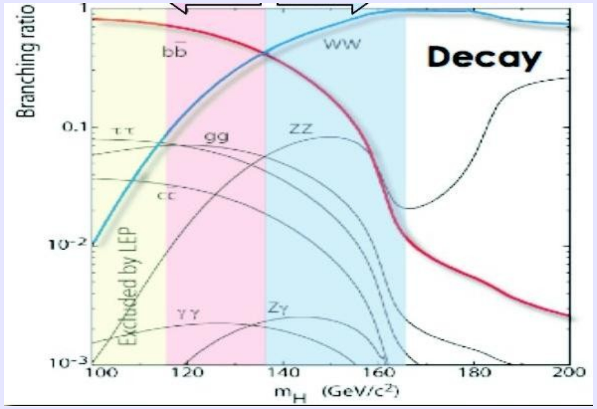






For M_H<135 GeV H→bb favored decay

For M_H>135 GeV H→WW favored decay



At M= 120 GeV

σ(WH)xBR=0.104 pb

σ(ZH)xBR=0.064 pb

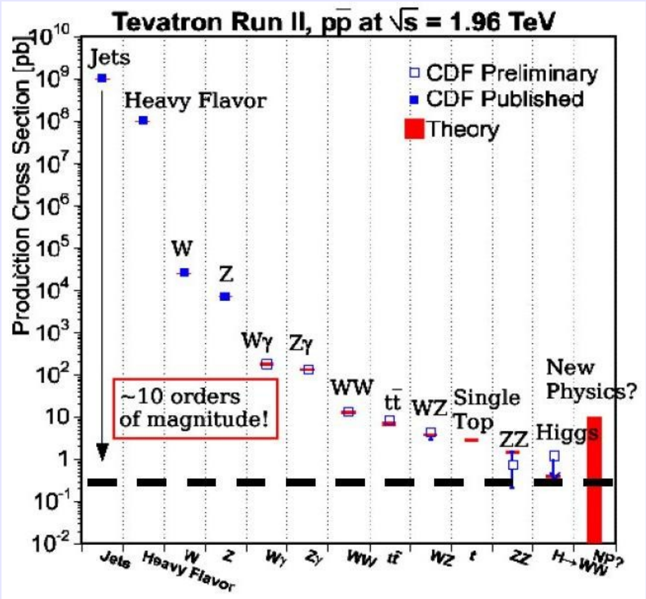
σ(Wbb)=40 pb

σ(t t) = 6.8 pb

At M=160 GeV

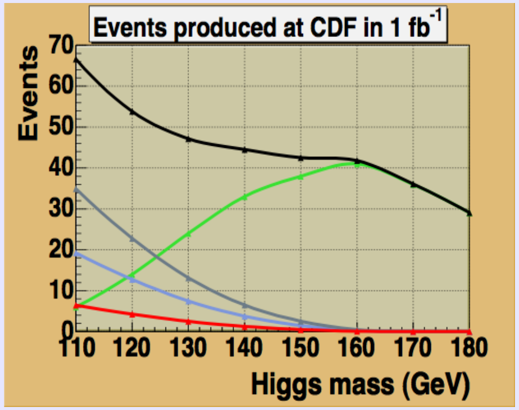
H→WW sig =9.5 ev

bkg=661 ev



Higgs Searches

Searches are becoming sophisticated : new tools are being used



- Increase lepton acceptance:
  - Use isolated tracks in μ or e ID gaps
  - Add other triggers
  - Increase acceptance by 25% for μ (WH)
  - Increase acceptance by 7% for lep. (WW)
- Neural Network b-tagging to reduce mistag and charm jets
- Use Matrix Element Integration to distinguish signal from background

$$P(\vec{x}_{obs}) = \frac{1}{\langle\sigma\rangle} \int \frac{d\sigma_{th}(\vec{y})}{d\vec{y}} \, \varepsilon(\vec{y}) \, G(\vec{x}_{obs}, \vec{y}) \, d\vec{y}$$

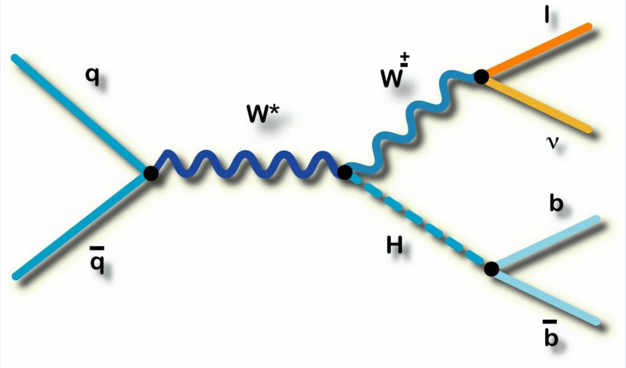
Matrix Element **Transfer functions** **parton level quantities**

- Use Multivariate approach (Neural Network) to separate signal from background

WH→lνbb

Selecting W+2jets events:

- 1 Isolated high P_T lepton (>20 GeV)
- Large missing E_T >20 GeV
- 2 jets with E_T>20 GeV and |eta|<2
- B-tagging: 2b(tight+loose) + 1b(tight)

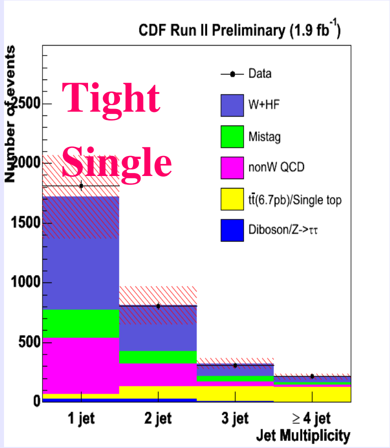


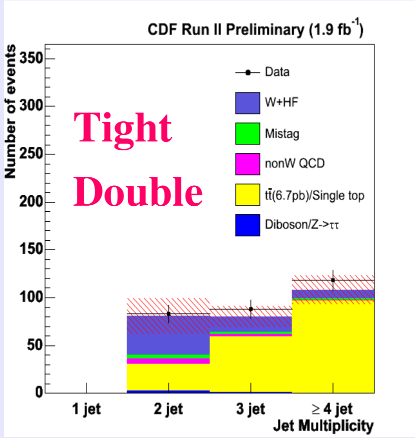
Main Backgrounds

W+ bb,cc : dominant

- Wqq' mistag
- Non-W QCD
- t t, single t, WW, WZ

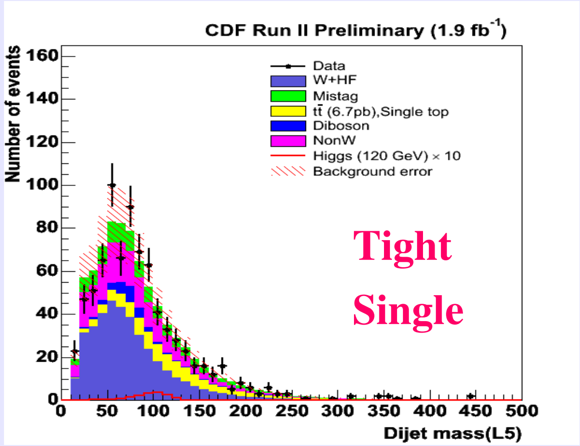
Verify background calculation on all jet multiplicities

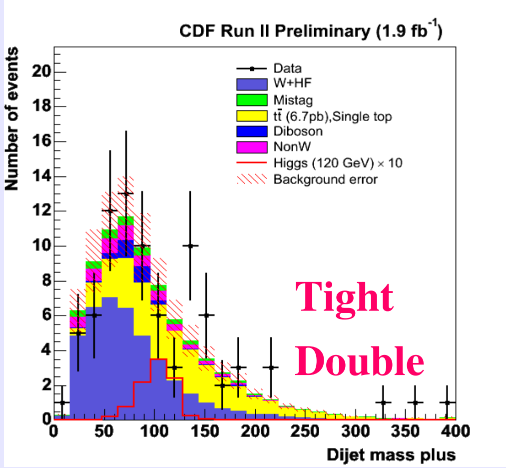


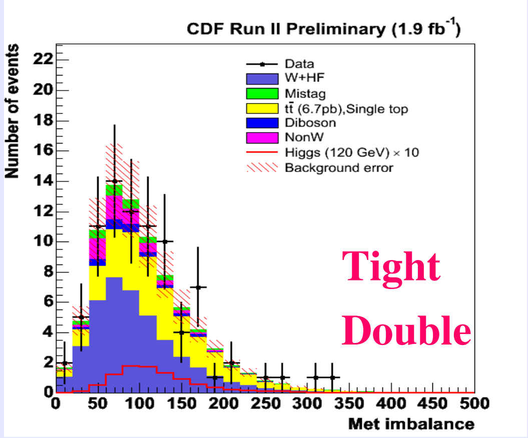


$WH \rightarrow l\nu bb$

- Two-jet mass distributions show no excess (Tight refers to b-tagging)

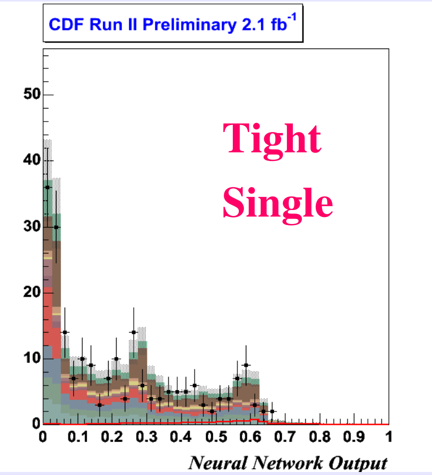


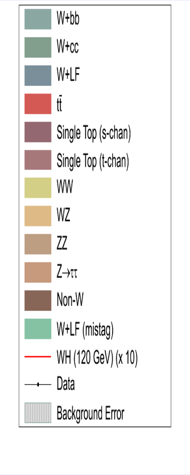


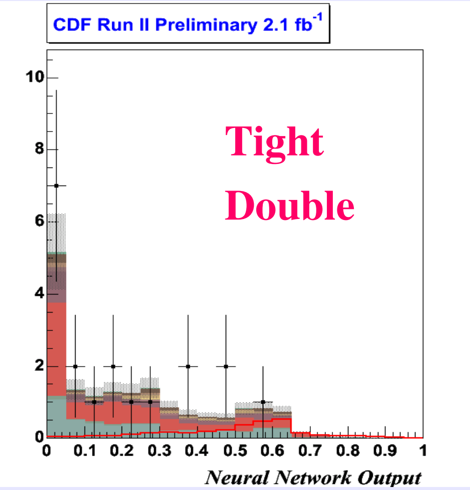


- Data consistent with SM backgrounds

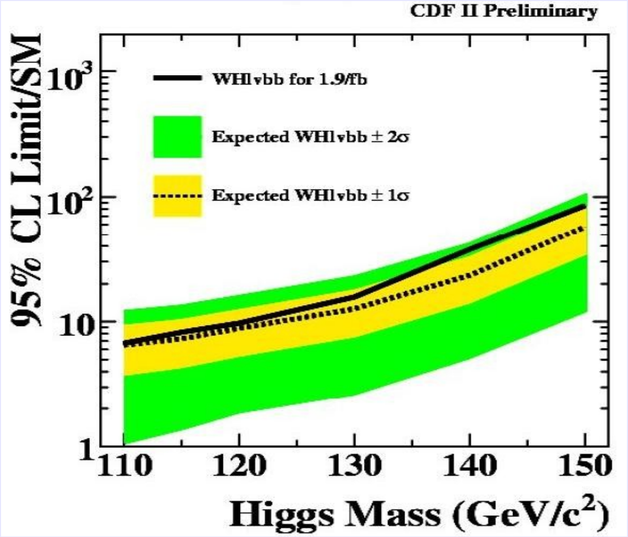
- Discriminant:
- M_{jj} P_T^{imb} P_T^{sys}
- $M_{l\nu j}^{min}$ $Dr_{l\nu}$ E_T^{jets}







WH → lνbb Low Mass Limit



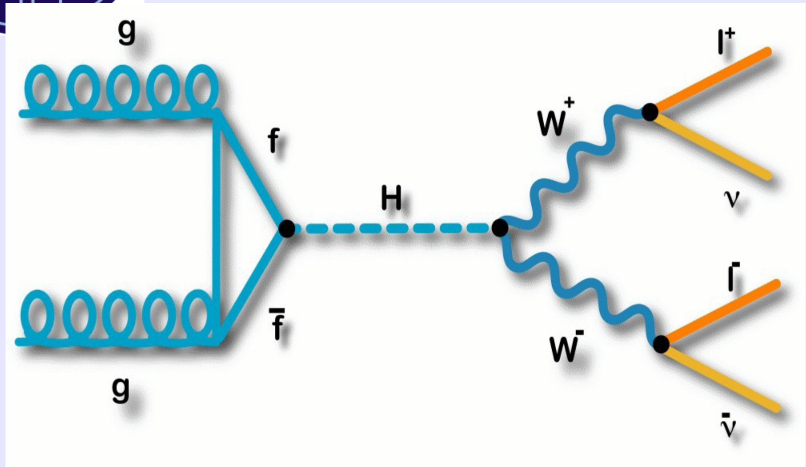
2.1 fb^{-1} limit at M_H=115 combining all 6 classes of events:

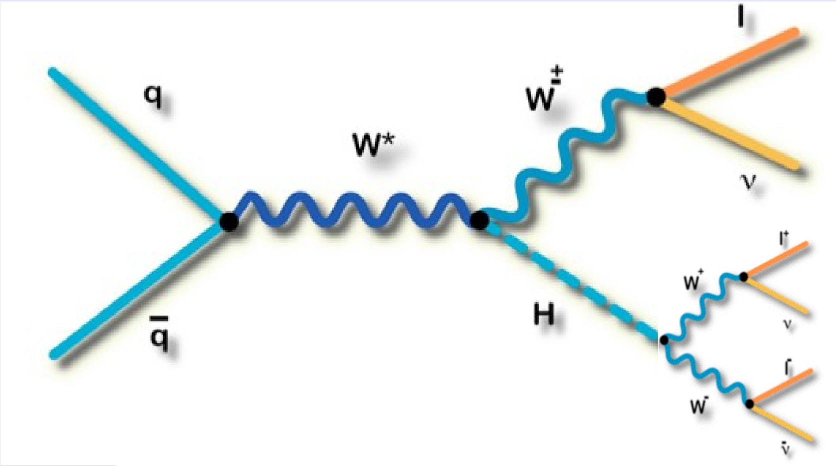
Observed/expected limit: 6.4/6.4xSM at M_H=115

For low Higgs mass many channels have been studied.
They all contribute to the final limit (see later)

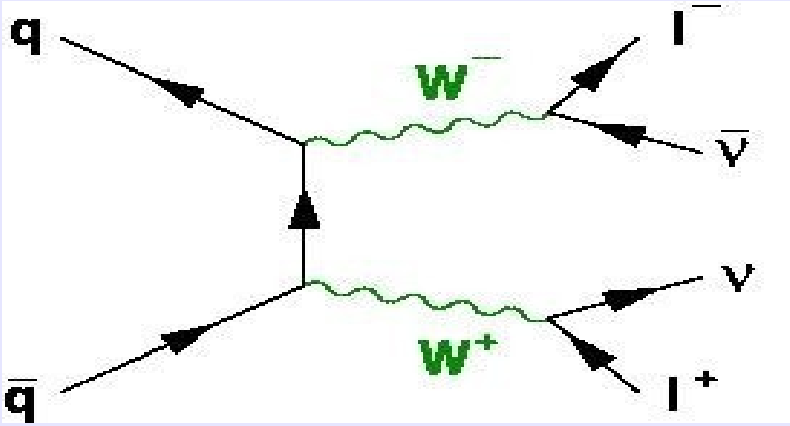
WH	l ν b b	~40%
ZH	l l b b	~10%
ZH	ν ν b b	~40%
WH	(l) ν b b	~10%
VH	τ τ + 2 jets	~10%
VH	j j b b	~10%

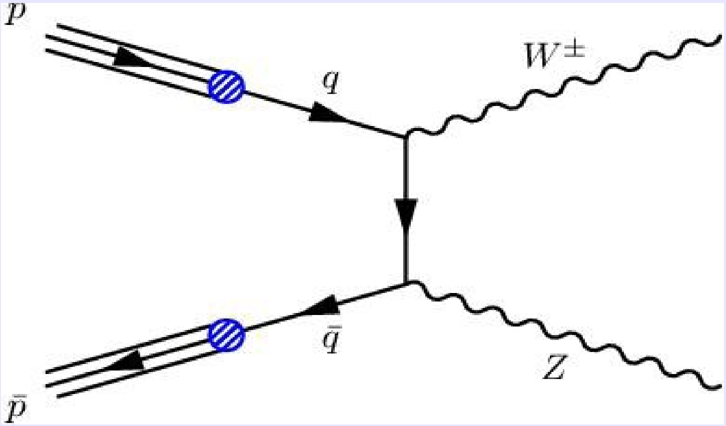
High Mass Higgs Signatures





- $H \to WW \to ll\nu\nu$: 2 opp-sign Leptons + Met
- $WH \to WWW^{*} \to l^{\pm}l^{\pm}\nu\nu X$: 2 same-sign Leptons + Met
- Major backgrounds: WW, WZ, ZZ, top, QCD…

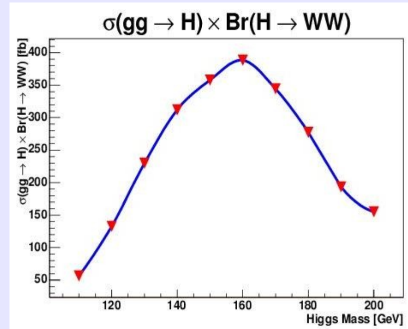




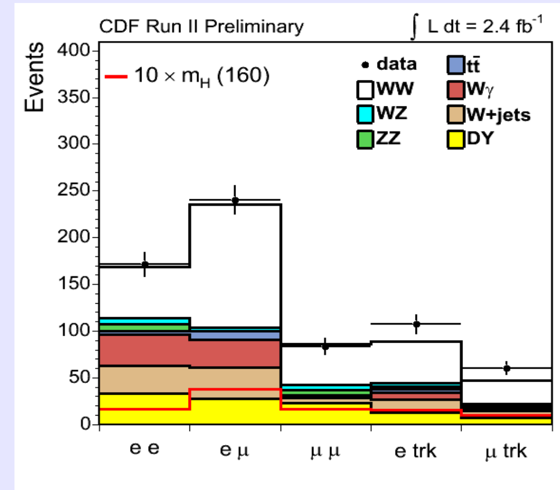
Higgs → WW→ l ν l ν

Event selection:

- 2 OS leptons,
  P_{T1} > 20, P_{T2}>10 GeV
  (use ISOTR + good ID)
- N(jets) ≤ 1
- MET > 20 GeV



acceptance for both W into leptons: 6%



H→ lνlν expect 9.5 ± 1.1 signal events in 2.4 pb^{-1}

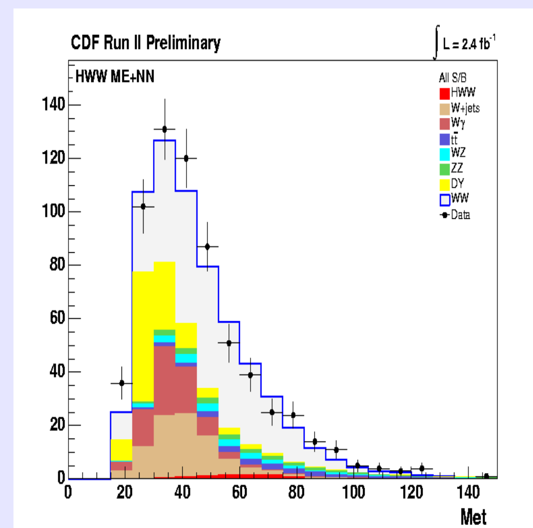
Backgrounds:
WW
DY
Wγ
WZ
WH

CDF Run II Preliminary $\int \mathcal{L} = 2.4\,fb^{-1}$

$M_H = 160\ GeV/c^2$

$H \to WW$	9.5	±	1.1
WW	300.3	±	38.1
WZ	20.5	±	3.1
ZZ	18.2	±	2.7
$t\bar{t}$	20.8	±	3.8
DY	104.0	±	23.0
$W\gamma$	72.4	±	18.7
$W+$jets	89.2	±	22.8
Total BG	**626**	±	**54**
Data	**661**		

HWW ME+NN

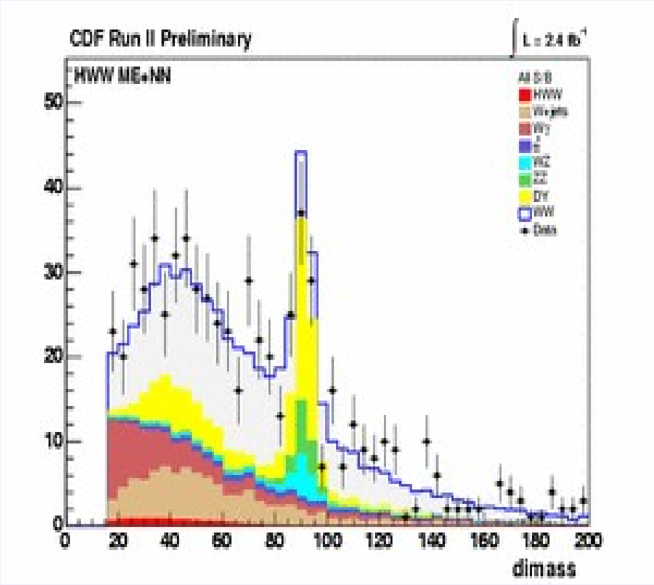


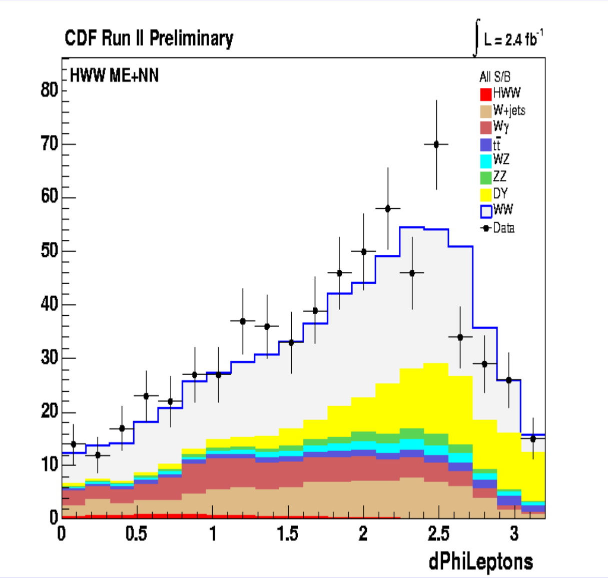
Higgs → WW → lν lν

Analysis based on ME integration + NN discriminant

$$P(\vec{x}_{obs}) = \frac{1}{\langle\sigma\rangle} \int \frac{d\sigma_{th}(\vec{y})}{d\vec{y}} \, \varepsilon(\vec{y}) \, G(\vec{x}_{obs}, \vec{y}) \, d\vec{y}$$

Use ME for 5 background processes:
HWW, WW, ZZ, Wγ, W+jets





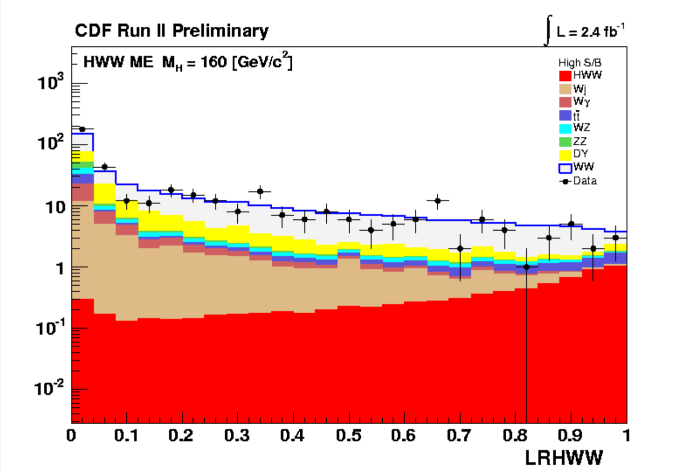
Higgs → WW→ lνlν

NN discriminant: LRNN+Kinematics

LRNN includes:

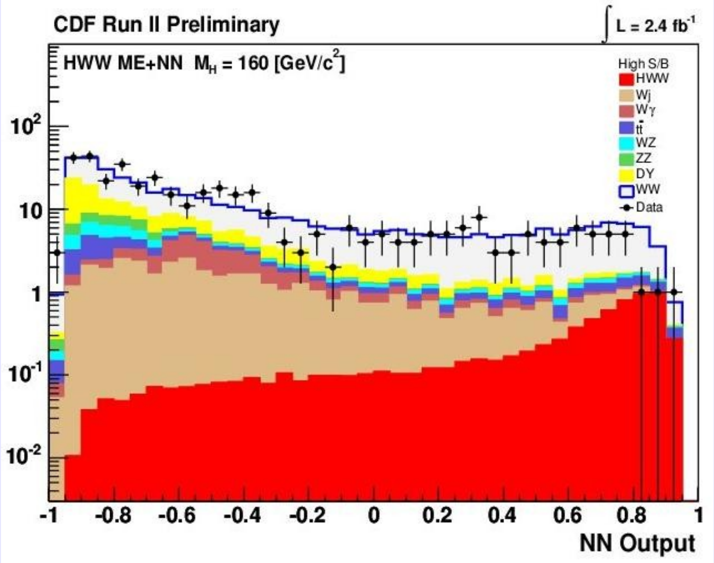
5 Matrix Element likelihood ratios

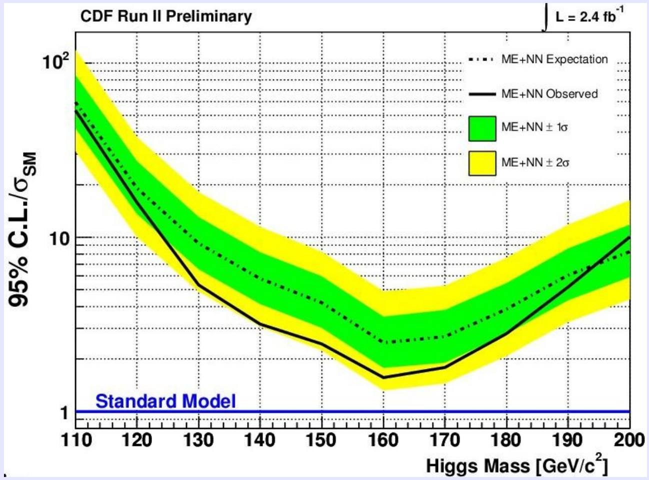
$$LR_m = \frac{P_m(\vec{x}_{obs})}{P_m(\vec{x}_{obs})+\sum_i k_i P_i(\vec{x}_{obs})}$$



Final NN: add kinematics

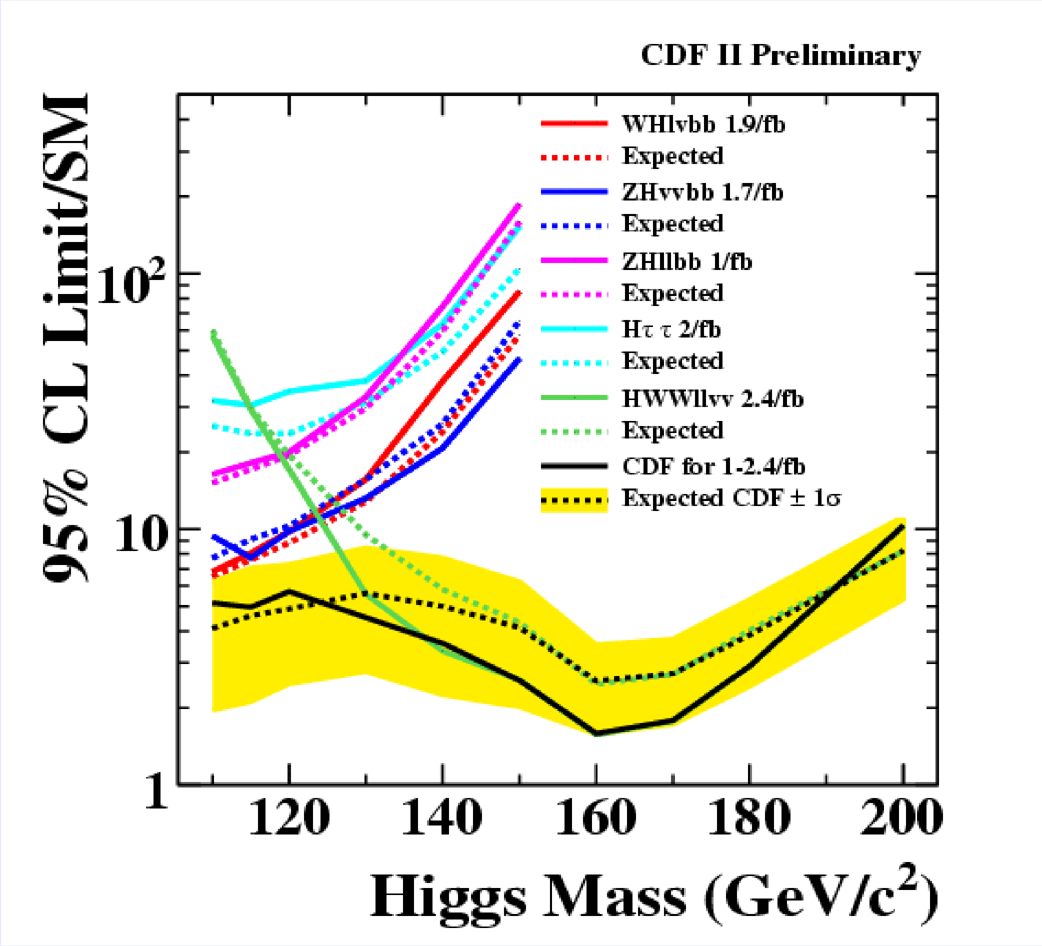
MET, $\Delta\Phi_{ll}$, ΔR_{ll}, m_{ll}





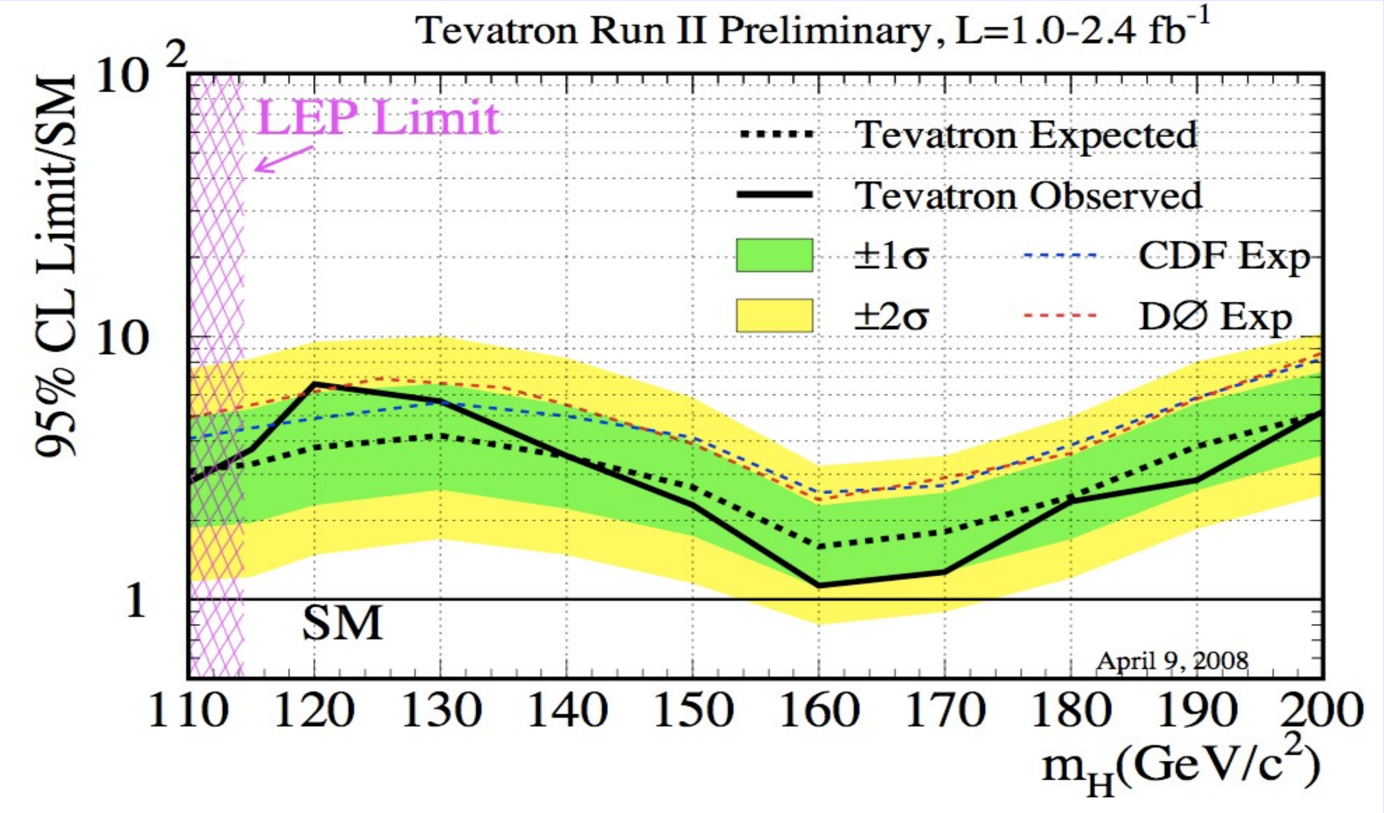
obs/expected limit is 1.6/2.4 x SM

Summary of CDF Higgs limit



observed/expected 5.0/4.5 x SM at M=115 GeV/c^2
observed/expected 1.6/2.6 x SM at M=160 GeV/c^2

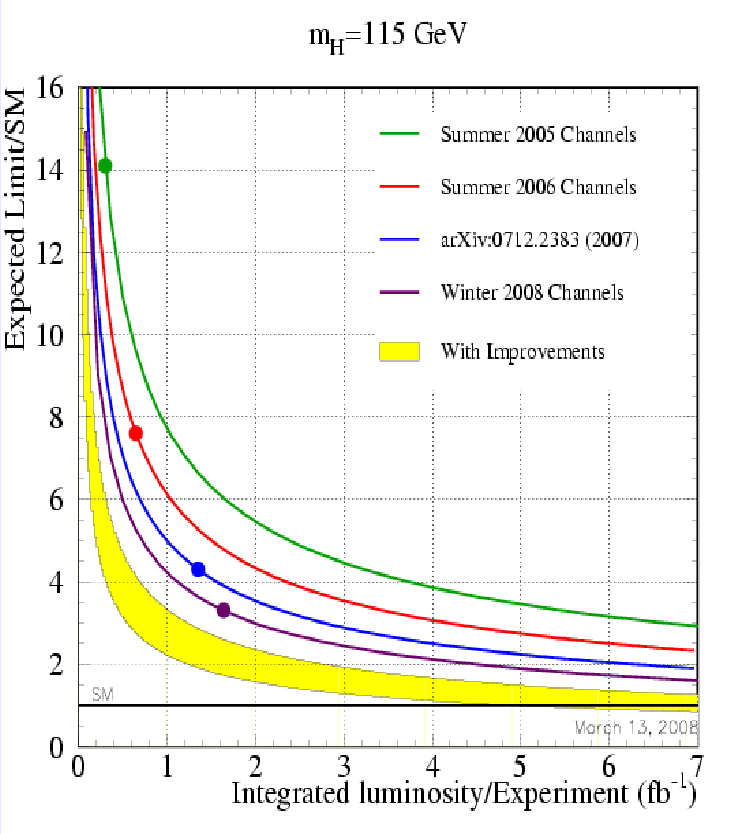
Combined CDF- DØ Higgs limit

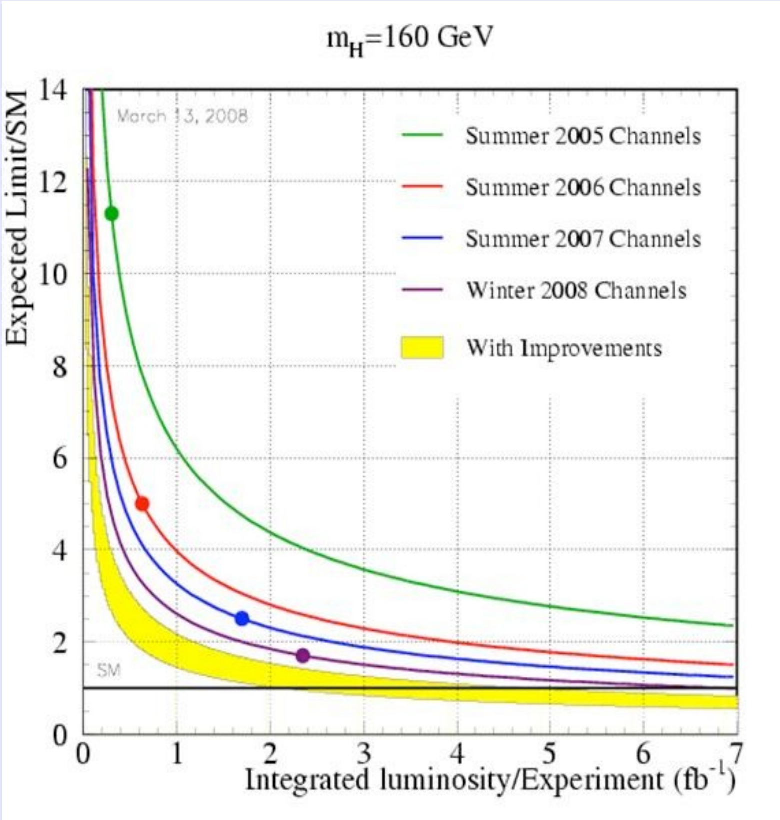


observed/expected 3.7/3.3 x SM at M=115 GeV/c^2

observed/expected 1.1/1.6 x SM at M=160 GeV/c^2

Tevatron Sensitivities

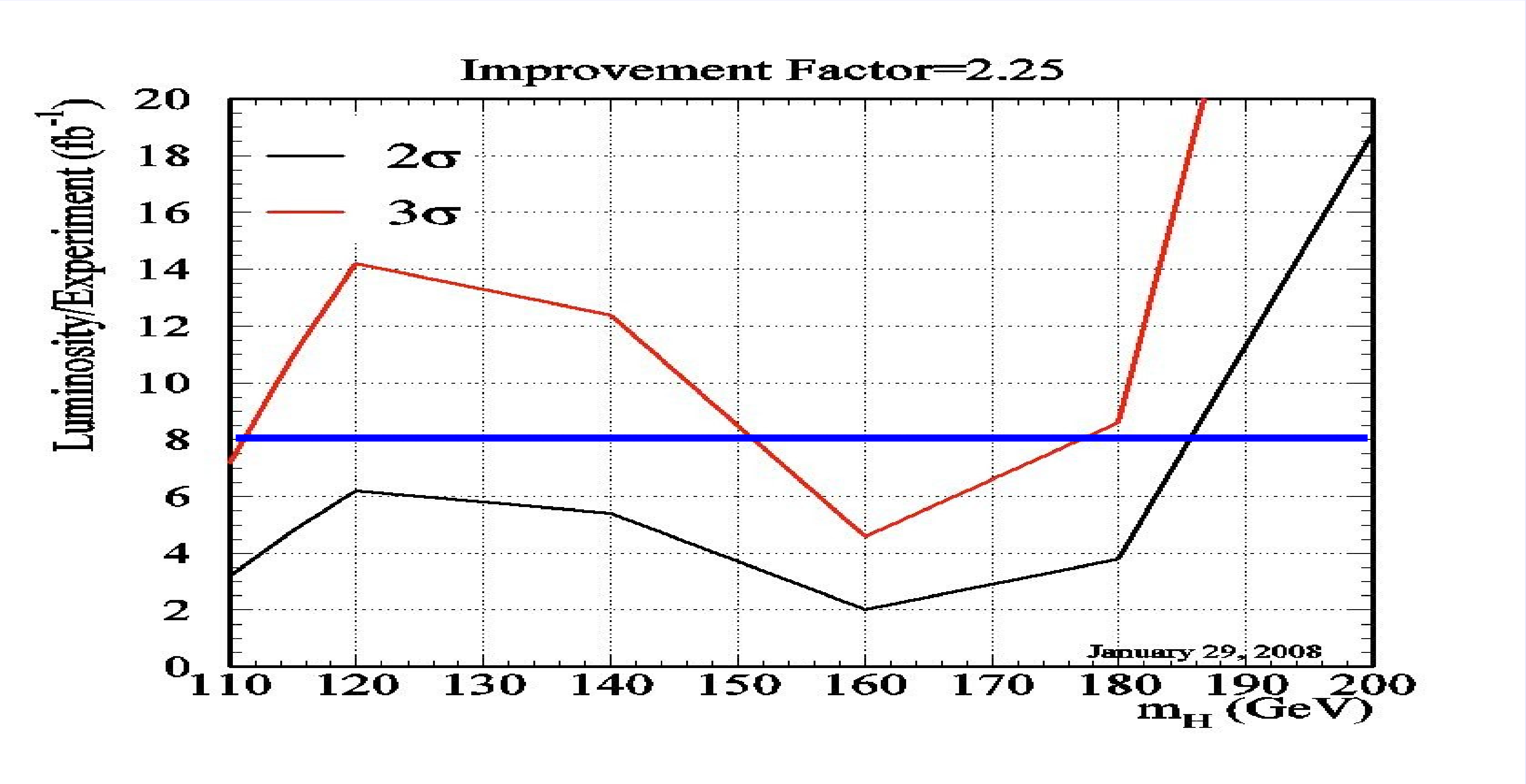




Higgs Sensitivity improves better then 1/sqrt(L)

- with more data, new handles
- more advanced analysis techniques

Future prospects



With 8 fb^{-1} of data by 2010, CDF and D0 could

- either exclude Higgs with M_H<185 @ 95% CL
- or find 3σ evidence for Higgs near M_H=260 GeV/c^2

Summary

- Tevatron doing well: increasing integrated luminosity rate, may run to 2010 (depending on funding)
- CDF is taking lots of data and can sustain data taking and analysing through 2010, if the run is extended
- Results on top properties coming out continuously: no deviation from SM observed as yet
- Top mass measurement has a 1.8/171.4 =1.1% precision Statistical and systematic uncertainties are ~ equa l
- Higgs searches are very active: improving the methodology to obtain limits at a faster rate than by adding data
- Of course, with LHC starting soon, the saga will continue!!

BACKUP SLIDES

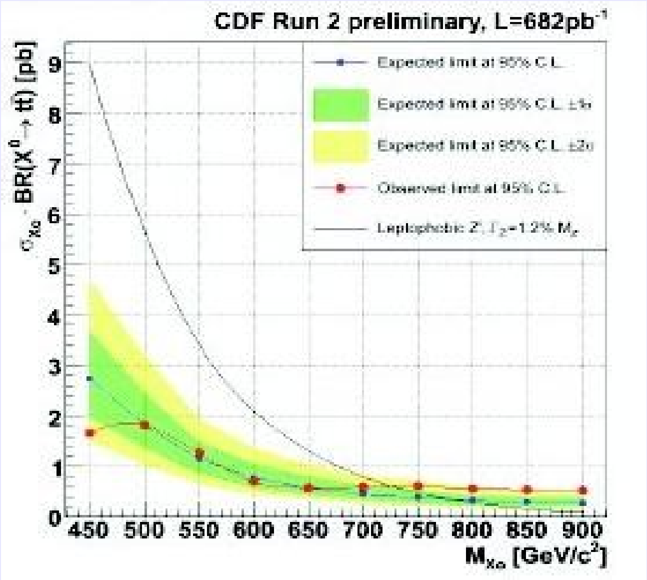
MORE INFO

Non-standard Top production

Search for resonant $t\bar{t}$ states

$pp \rightarrow X^0 \rightarrow t\bar{t}$

Reconstruct the $t\bar{t}$ system by ME techniques, then test for excess

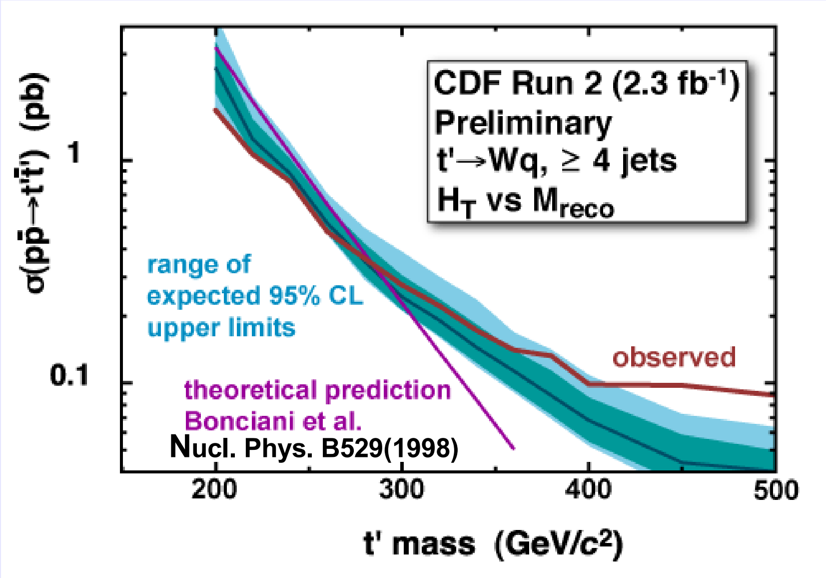


Exclude topcolor Z' (Γ=1.2%M_{X0}) for M_{X0}< 725 GeV/c^2 @ 95%CL

Search for heavy top, 4th generation

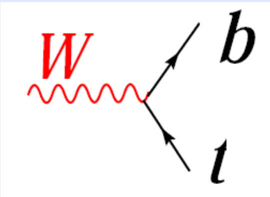
$t' \rightarrow W q$

Motivated by BSM models
2D fit of H_T -vs M(t t)



Exclude for $M_{t'}$< 284 GeV/c^2 @ 95%CL

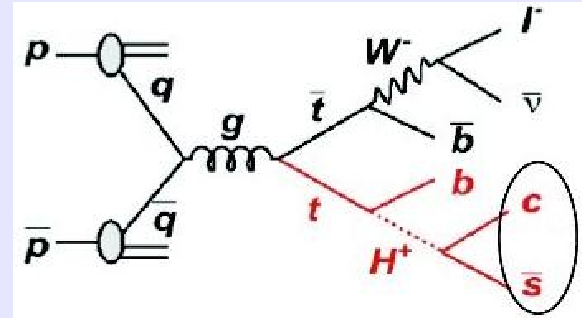
Top into H^+ Search



$|V_{tb}|$~0.99

Search for:

$t \rightarrow H^+ b$

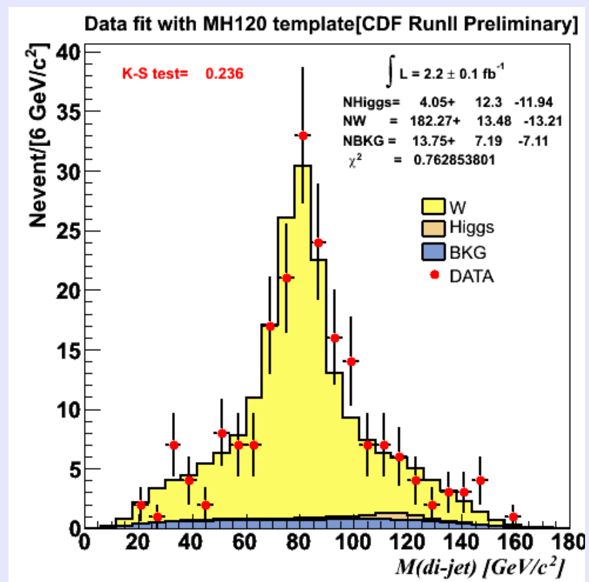


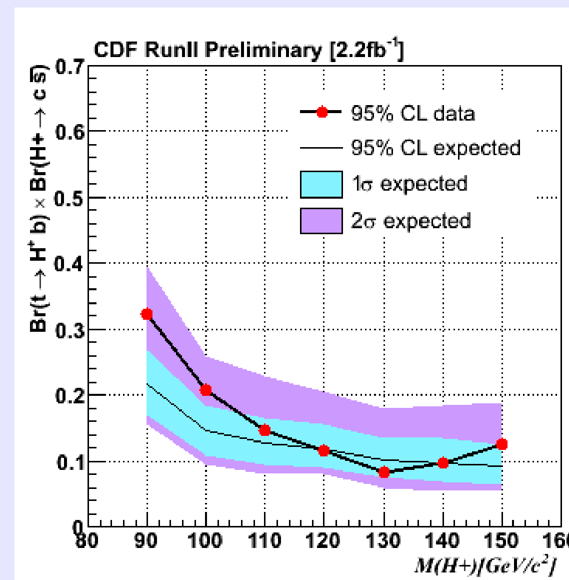
MSSM predicts $H^+ \rightarrow cs$ for $\tan\beta < 1$

Assume $BR(H^+ \rightarrow cs) = 1$

2.2 fb^{-1}

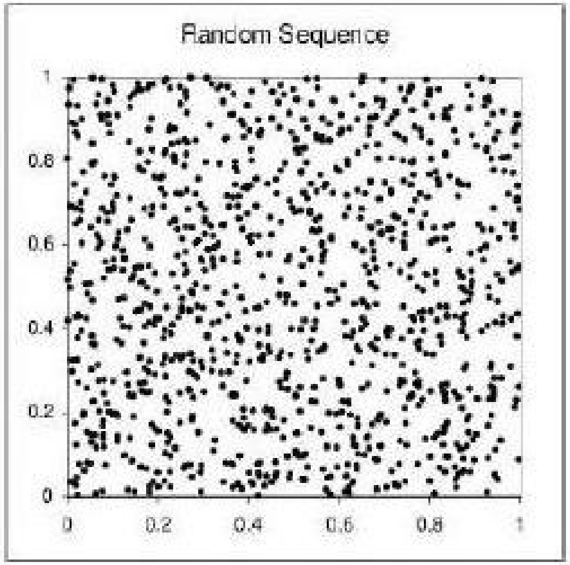
Fit dijet invariant mass with W and H+ templates, assuming 10% $t \rightarrow$ H+ decay.

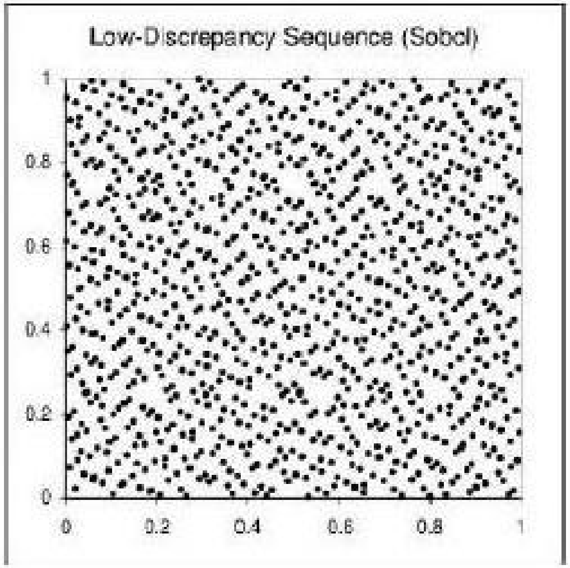




No evidence found

Quasi-MC Integration





- Best integration method in high dimensions. Started seeing significant practical use in late 80s. To our knowledge, the first study of QMC for HEP-related integrals was published in 2006 (by Kleiss and Lazopoulos).

- Quasi-MC integration uses "low-discrepancy" sequences (we use a variant of the Sobol sequence, plotted on the left) to provide more uniform coverage of the phase space.

- For "well-behaved" functions, convergence rate is guaranteed to be at least as good as $O(\log(N)^d/N)$. Compare with $O(1/\sqrt{N})$ for standard MC.

- We use QMC for 18 dimensions out of 19. Convergence is estimated empirically, from the smoothness of the likelihood curves.